ON THE AIRPORT GATE ASSIGNMENT PROBLEM

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Summary

While working with proper modeling techniques and solving methodology, it is possible to achieve an efficient and practical Integer Programming (IP) model that targets a good solution for the Airport Gate Assignment Problem (AGAP). In this thesis, we presented the IP modeling methodologies coupled with searching algorithm to deal with the AGAP problem of both the daily planning stage and real-time recovery. We introduced our 3-terminal AGAP model, Multi-terminal AGAP Model, Multi-pier AGAP Model and an improved Linearized Quadratic AGAP Model. These works have been proved to be much more efficient and possible to be applied in practical problems. According to the experiment results our proposed models can produce good solutions while also incorporating the consideration for transfer passengers.

In addition, we also proposed a systematic model-combined two-stage Real-time Recovery Policy to cope with the real-time flight schedule disruptions, which have not been covered in the literature. To analyze the methodologies to solve the real problems, we have extended the research to incorporate more practical performance criteria of the airport and applied them on the actual data from one international hub airport. With proper modeling techniques and research assumptions, we have found that IP modeling can be applied to the real-life large-scale AGAP problem while satisfying more practical performance criteria that are not included in previous literature.

Nomenclature Table

α : the weight of the importance of the baggage handling to the passenger walking distance;

ε_e : the passenger walking distance from terminal 1 to terminal e (e=2,…E);

θ : a sufficiently large number to make sure that the change of the original flight-gate assignment will have a high cost in the objective function;

a : taxi-way area;

A_i : the set of flights that belong to conflicting airlines that can not be adjacent with the airline of flight i ;

A_a : the set of gates in taxi-way areas a ;

B_i : the set of large aircrafts that can not be parked as neighbors with aircraft i ;

C_a : the traffic capacity of the taxi-way area a so as not to cause aircraft taxi-in and taxi out traffic congestion;

CM_p : the set of the common-room gates at common room areas p ;

CR : the set of critical flights;

CR_i : the set of connecting flights with critical flight i ;

d_{12} : the passenger walking distance between terminals 1 and 2;

d_{13} : the passenger walking distance between terminals 1 and 3;

d_{23} : the passenger walking distance between terminals 2 and 3;

d_e : the adjusted distance where $d_1 = \frac{(d_{12} + d_{13} - d_{23})}{2}$; $d_2 = \frac{(d_{12} + d_{23} - d_{13})}{2}$;

$d_3 = \frac{(d_{13} + d_{23} - d_{12})}{2}$;

D_j^a : walking distance for arriving passengers from gate j to the baggage claim area;

D_j^d : walking distance for departing passengers from check-in point to gate j;

$D_{jj'}$: the walking distance from gate j to j';

D_j^t : the average walking distance for transfer passengers at gate j;

DT_i : the set of flights that have the same departure time with flight i;

DP_i : the set of flights whose departure time is within the common-room gate usage time after flight i's arrival;

e: terminal;

E: the total number of terminals;

G_{ij} : equals to 1 if $j \neq$ the original gate for flight i; 0 otherwise;

H_j^a : the arrival passenger's baggage handling distance from gate j to the baggage claim area;

H_j^d : the departure passenger's baggage handling distance from check-in point to gate j;

H_j^t : the transfer passenger's baggage handling distance from gate j to the baggage sorting center;

i, i': flight;

I_i : the set of flights that have overlapping ground time with flight i;

I_{ca} : the flight sets c where more than C_a flights have overlapping ground time;

I_s : the set of (i,t) of flights with delay choices that has ground time overlap at checking time point s;

j, j': gate;

K : the total number of remote stands;

M : a sufficiently large number; larger than θ in the Real-time Gate Recovery Model to make sure that flights will be assigned to remote stands when there is no gate l_i^e : equals to 1 if flight i is assigned to terminal e; 0 otherwise;

n : the total number of fixed gates;

N_j : the set of the neighbor gates of gate j;

NR_j : the set of the nearby gates of gate j;

P_i^a : number of arriving passengers of flight i;

P_i^d : number of departing passengers of flight i;

P_i^t : the total number of transfer passengers from flight i;

$P_{ii'}$: the number of transfer passengers between flights i and i' ;

P_i : the total number of passengers of flight i;

r : the time point;

r_i^a : the time flight i arrives at a gate;

r_i^d : the time flight i departs a gate;

$\{R\}$: Non-reassign Flight Set;

s : the checking time point;

t : the delay time choice;

T_e : the set of gates at terminal e;

W_{ij} : the airline's gate preference weight of flight i for gate j;

X_{ij} : the decision variable, equals to 1 if flight i is assigned to gate j, 0 otherwise;

X_{ijr} : the decision variable; equals to 1 if flight i is assigned to gate j at time point r; 0 otherwise;

X_{ijt} : the decision variable; equals to 1 if flight i is assigned to gate j with a delay time t and 0 otherwise;

$y_{ii'}{}^{e}$: equals to 1 if one of the flights i and i' is assigned to terminal e and another is assigned to a different terminal; 0 otherwise;

$y_{ii'}$: equals to the cross-terminal transfer walking distance between flights i and i';

$Y_{iji'j'}$: equals to 1 if flight i is assigned to gate j and flight i' is assigned to gate j', 0 otherwise;

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Chapter 1 Introduction

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Challenges in Practical Implementation of IP Models

Overview of the Contents

1.1 Background

Airport gate assignment has been an important piece of works at airport for many years. The assignment affects the service standards for not only passengers but also airlines and cargo services. These service standards are some of the important criteria to evaluate whether the service of an airport is good. The airport authority needs to plan a good aircraft-to-gate assignment solution to satisfy these criteria.

In general, a passenger would not like to walk a long distance to reach his destination in the airport. The walking distance can be the distance from the check-in point to a gate or from a gate to the baggage claim area or from a gate to another gate depending on whether he is an arrival or departure or transfer passenger. The distance a passenger has to walk in an airport has been an important performance measurement for an airport. In the case of transfer passengers, it is important to assign the destination aircraft to a nearby gate if the connecting time is short. Otherwise transfer passengers may not be able to reach the connecting flight in time. We call such short-time connections "critical transfer" to distinguish from the other types of transfer. Thus to improve the performance of an airport we not only need to minimize the total walking distance of all the passengers but also try to minimize the connecting time for critical transfers by assigning critical transfer flights to nearby gates.

Certain airlines may prefer their aircrafts to be assigned to certain gate areas if possible so that it is convenient for their operations and allocation of personnel. Also, there are normally more than one ground service providers in an airport that would have contracted airlines to their services so that they would like the aircrafts of their contracted airlines to be assigned to gates near their service center area. Thus flights of different airlines are preferred to be assigned to different gate areas.

A good assignment may also need to consider the baggage handling efficiency. To assign aircrafts to gates that reduce the baggage handling distance is an important criterion in busy airports. However, as airports also need to consider passengers' convenience, the airport authority also needs to consider the importance of improving baggage handling efficiency versus minimizing passengers' walking distance. For a big airport where baggage handling is a major problem, baggage handling efficiency may be a more important criterion.

During peak hours, where a large number of flights arrive or depart at about the same time, traffic congestion may occur at taxi-way if these flights are assigned to gates close to one another. An aircraft may have to wait for the taxi-out of another aircraft.

Thus, a good Airport Gate Assignment solution is not only to seek a feasible flight-to-gate assignment but also to try to provide more convenience to passengers, to satisfy the requests by airlines, to make the baggage handling process more convenient for ground services providers and also reduce the taxi-way traffic congestion in the airport, as well as many other aspects not discussed here. There are many methodologies used to solve the Airport Gate Assignment Problem (AGAP), such as Mixed Integer Programming (MIP) modeling and knowledge-based Expert Systems. However, these methodologies have their own advantages and challenges in their practical implementation. Solving the problem effectively and efficiently is a major concern to the airport authorities and researchers.

1.2 Challenges in Practical Implementation of IP Models

There has been a dramatic progress being made in the solution methodology of Integer Programming (IP) for practical problems in recent years. Many researchers have proposed different solution methodologies. Some of them focus on MIP problems while others focus on problems such as pure Binary Integer Programming problems. More and more practical problems in the real world can be solved using IP methodologies as the efficiency of the methodologies improves. New algorithmic breakthroughs in IP always generate new research and development of the solution methodologies, which can also be reflected in some of the sophisticated software packages for IP such as IBM’s OSL, CPLEX etc. The development of such sophisticated IP software greatly improves the application of IP in practical problems. Some successful implementations of IP models for the AGAP Problem have been reported, such as that of Taiwan Chiang Kai-Sek International Airport (Yan and Huo, 2001). However, solving the IP models in reasonable time for the real-life AGAP Problem is still challenging, as the computational time depends very much on the data structures and the number of criteria taken into account.

In reality, each airport has its own criteria and considerations for the flight-to-gate assignment. Such criteria and considerations may be based on the authority of the airport, airline requests, baggage handling processes etc. For example, some airports require certain airlines to be assigned to specific gate area, if possible, while some airports treat airlines equally. Due to the various conditions and considerations, such assigning constraints are numerous and each of them needs to be specifically modeled. As a result, the number of parameters and constraints for an IP model is usually very huge for real situations. In reality, the planning of the gate assignment schedule has to be completed within a reasonable time. If the complexity of the problem results in unreasonable solution times for solving the IP model, the using of IP model may not be practical approach. Many researchers have resorted to proper modeling techniques, mathematical methodologies and heuristics to improve the efficiency of the solution. Another factor that cumbers the implementation of the IP model to the AGAP Problem is that the IP modeling of the problem needs specific knowledge of OR and IP modeling methodologies. As a result, Expert Systems, or Knowledge-based systems, which are typical methodologies in computer science, are popular in solving the airport gate assignment problem for daily flight-to-gate assignment, as can be seen from the work of Hamzawi (1986), Gosling (1990), Su (1993) etc. Expert Systems have been successfully applied to many problems that are combinatorially explosive in nature to get a faster generation of the solutions. It is particularly suitable when the use of heuristics to generate a 'satisfying' solution is appropriate. Instead of using optimization methodologies, many researchers have explored the faster generation of solutions through the pruning of search spaces and the use of heuristics to meet up with the need to find a satisfactory solution.

However, Expert Systems are used for seeking satisfactory, but not necessary optimal, solutions, as stated by Muthukrishnan and Srihari (1991). There is no guarantee that Expert Systems can avoid being trapped at a near-optimal solution. In practice, it is difficult to tell how far the 'satisfying' solution is from optimality. The most difficult part of the problem is in identifying the rules to guide the assignment process, because of the large number of factors to be taken into account as pointed by Su and Srihari (1993). These factors may make the searching heuristic difficult to structure and this may in turn affect the quality of the solution.

1.3 Overview of the Contents

In the following chapter, we summarize the literature review of the previous works and provide insights to some of the major works. In Chapter 3, we extend our discussion to the extended model that reflects the criteria and constraints in a real-life AGAP problem. We introduce our proposed new models, which include the 3-terminal AGAP Model, the Multi-terminal AGAP Model and the Converted Linearized Quadratic AGAP Model and give the corresponding illustrations and comparisons through the case study in Chapter 4. The Real-time Gate Recovery Policy and the IP Gate Recovery Model are then presented in Chapter 5. We also summarize our case study using the practical data from an international hub airport for the IP Gate Recovery Model and the Real-time Recovery Policy in that chapter. Conclusions are made in Chapter 6.

Chapter 2 Literature Review

Topics in this chapter:

Introducing Airport Gate Assignment Problem

Overview of Previous Work

Basic Airport Gate Assignment Model

Linearized Quadratic Airport Gate Assignment Models

2.1 Introducing Airport Gate Assignment Problem

Airport Gate Assignment Problem, the assignment of arrival and departure aircrafts on schedule to available gates, is a major issue during the daily airport operations. In practice, the airport authority faces two kinds of assignment problems: planning stage assignment and real-time reassignment.

Given the flight schedule of each of the airlines in operation at the airport, the airport authority needs to define which aircraft should be assigned to which gate, normally on a 12 or 24 hour basis, that is, the planning of the flight-to-gate assignment should be 12 or 24 hours earlier. This is the planning stage assignment for the AGAP Problem. As there may be many flights of different airlines in operation at the airport, flight schedule changes are likely to be frequent, even though the flight schedule normally has been released by airlines a number of days in advance. Thus, instead of weekly or monthly planning of the gate assignment, the airport authority normally performs a daily planning. The planning of the assignment is scheduled during non-peak hours such as mid-night so that there is enough time for the preparation and practically this allows more time for the running of the gate assignment program, which is time consuming for a large international airport.

In the daily planning stage for the flight-to-gate assignment, the distance that a passenger is required to walk in an airport to reach either the departure gate, the baggage claim area, or the connecting flight is an important criterion in effective utilization of fixed aircraft gates at an airport terminal. To provide passengers with better services, the airport authority needs to assign the aircrafts to gates so as to reduce the walking distance of passengers, especially for transfer passengers who need to take the connecting flight in a short period of time. During peak hours at the airport, an extreme case for that airport is when there are more flights than gates within a certain time slot, resulting in not enough fixed gates for all the aircrafts. In such a case, some of the aircrafts may have to be assigned to remote stands. Passengers will thus have to face the inconvenience of taking shuttle buses to get to the terminal building instead of using the aerobridge of the fixed gate. The airport authority needs to avoid such situations from happening in practice. In addition, due to the increasing number of flights and deregulation of flight arrivals, the baggage handling process becomes more demanding. The airport authority prefers to find a way to facilitate the baggage handling process as well. These criteria make the work of daily planning of the AGAP Problem challenging for the airport.

Another type of Airport Gate Assignment work is in the Real-time Gate Recovery due to the flight schedule disruptions, i.e., to adjust the flight assignment due to the changes of the original daily flight schedule. Real-time recovery work is challenging for the airport because the original assignment has already been done and changes of arrival or departure time may make the original assignment infeasible or affect many flights, especially when flight schedules are tight. Moreover, the disruptions of the flight schedule that happen in the near future may affect the ground service providers' preparation at the gate, which is dedicated to certain airlines and certain aircraft types. Instead of minimizing the walking distance of passengers, the objectives of the Real-time Gate Recovery are to minimize the disruption of the original assignment as well as minimizing the passengers' delay. In addition, if a disruption happens in the near future, the airport authority may also need to consider the possible impact of the gate changes to the ground service providers' preparation at the gates.

According to the literature to date, all the work for AGAP problem focused on the flight-to-gate assignment at the planning stage. There has not been any work that we know of in the area of real-time gate recovery, which we have made a thorough analysis and proposed a systematic way to solve the problem.

2.2 Overview of Previous Work

One of the earliest efforts to use quantitative methods incorporated with a design process to minimize the intra terminal travel was presented by Braaksma and Shortreed (1971). Wirasinghe et al. (1987) extended the work in this area and proposed a method to calculate walking distance involved in the multi-pier terminal geometry. In their work, they also presented a method to evaluate the optimal geometry for an airport based on passenger walking distance. Robuste (1988) extended the work to hub-terminal transfer of passengers and baggage respectively. Bandara (1989) followed the work of Wirasinghe et al. (1987) and introduced more terminal types, hub transfers, unequal piers, etc, and also proposed some guidelines in the airport preliminary terminal design to generalize the conclusion. According to a certain traffic volume and passenger composition, Bandara and Wirasinghe (1992) proposed ways to evaluate the suitability of airport terminals. These became part of the airport terminal design process as well.

While many works are based on the optimization of the preliminary design process for the airport terminal, other researchers, such as Babic et al. (1984), Mangoubi and Mathaisel (1985) etc., tried to solve the AGAP problem through Operation Research and IP modeling approaches. In such approaches, the total passenger walking distance is based on the volumes of arrival and departure passengers, volumes of transfer passengers, gate-to-gate distances, gate-to-baggage-claim distances, check-in-to-gate distances and aircraft-to-gate assignments, given a certain airport terminal layout. In the modeling of the problem, the cost associated with the assignment of the aircraft to gate depends on the distances from key facilities such as gates, check-in point and baggage claim areas, as well as the relationships among these facilities.

Babic et al. (1984) formulated the gate assignment problem as a linear 0-1 Integer Programming model. A branch-and-bound algorithm is used to find the optimal solution of the aircraft-to-gate assignment where the transfer passengers are not considered. Mangoubi and Mathaisel (1985) used an LP relaxation and greedy heuristics to solve the problem of Babic et al. They considered the transfer passenger walking distance based on a uniformly distributed gate-to-gate transfer pattern. Also, they formulated the problem as a linearized quadratic gate assignment model. However, they pointed out that it would be difficult and time-consuming to solve a linearized quadratic IP model, which included a huge number of variables and constraints. Thus they did not work further on the proposed model.

In the work of Haghani and Chen (1998), they proposed a linearized quadratic IP model for the gate assignment problem, where the transfer walking distance is the exact distance instead of being approximated by a uniformly distributed transfer pattern. By doing so, the problem complexity is increased greatly. Thus they introduced a heuristic to solve the problem, which is to obtain several sets of feasible solutions and then to choose the best one with the minimum walking distance. The heuristic was coded into C language and tested with several sets of experiment data. As the linearized quadratic model is a complex IP problem even for those with a small size, they used the cases of no more than 10 flights and 5 gates to compare the solution quality of their proposed heuristic with that of the optimal solution from the IP model. For large-scale problems, based on the improvements between the initial and final solutions obtained using the proposed heuristic, and the performance of the approach in other cases they concluded that the heuristic can provide close-to-optimal solutions to complex AGAP problems.

Another method is proposed by Yan and Huo (2001). In their model they introduced several delay choices to each flight. The delay choices are given to each aircraft so that it is possible for a flight to be assigned to a gate at different time points. The starting time for each flight to use the gate is flexible. These delay choices are modeled as different variables to each flight. For each flight there are several decision variables corresponding to it. In addition to minimizing the passenger walking distance, minimizing the total delay for all the flights is also included as part of the objective. When there are enough gate numbers for assignment, the delay choices for the flights are not needed. However, when there are insufficient gates, the delay choices may be useful in providing buffer time for flights to be assigned to gates. To efficiently solve large-scale problems in practice, the weighted method, the column generation approach, the simplex method and the branch-and-bound technique are used to develop a solution algorithm, which is applied in the case study concerning the operation of Taiwan's Chiang Kai-Shek airport.

Vanderstraetan and Bergeron (1988), Gosling (1990), and Muthukrishnan and Srihari (1991) worked on solving the gate assignment problem by using Expert Systems. An Expert system is a structured knowledge-based system. The aircraft-to-gate assignment procedure simulates the logic-based procedure of gate assignment by experienced experts at the airport. Instead of finding an optimal solution, it is used to find a feasible and satisfactory solution for complicated large-scale problems. Cheng (1997) proposed a knowledge-based airport gate assignment system that is integrated with mathematical programming. It is a process of utilizing the mathematical model to seek for a feasible solution while giving more control to the airport authority to change the importance of the criteria.

Other work based on simulation can be found in, for example, Cheng (1998) and Yan, Sheih and Chen (2002). While most of the works focus on improving the performance of static gate assignments, simulation can be used to analyze the interrelationship between the static gate assignment and the factors that may affect it. In the work of Yan, Sheih and Chen (2002), a simulation framework was proposed that not only can analyze the effects of stochastic flight delays on static gate assignments, but also can evaluate flexible buffer times and real-time gate assignment rules that the airport authority uses. A simulation based on airport operations at Chiang Kai-Shek airport is also used to evaluate the gate assignment performance.

Since the problem is NP-hard (Yan and Chang (1998)), many researchers tried various heuristic approaches to facilitate the solving process. Haghani and Chen (1998) proposed a heuristic that assigns flights with relatively more passengers to gates having smaller walking distance coefficients when there is no overlapping of the ground time of the flights. Xu and Bailey (2001) provide a Tabu search for the gate assignment problem. Their algorithm exploits the special properties of different types of neighborhood moves, and adopts an effective candidate list strategy.

As a lot of work has been focused on the AGAP Problem with the objective of minimizing the total passenger's walking distance, there is not enough emphasis on the baggage handling process, the special request by airlines, the taxi-way traffic congestion, and schedule disruptions. A thorough and detailed analysis of the operations at airport is necessary to increase the airport service standard for not only the passengers but also the airlines and ground service providers, which have been included in our work for the problem.

2.3 Basic Airport Gate Assignment Model

The basic AGAP IP model was proposed by Babi et al. in 1984. The objective in the model is to minimize the total walking distance for arrival and departure passengers. The modeling of the problem is based on the following information and assumptions:

1) The flight schedule indicating the aircraft arrival and departure time, which is assumed to be fixed;

2) The number of gates, which is assumed to be enough for any time slot of the planning horizon;

3) The number of passengers for each flight, including both arriving and departing passengers;

4) The airport terminal layout which indicates the walking distance from any gate to the baggage claim areas and the walking distance from the check-in point to any gate.

The model proposed by Babi et al. (1984) is as follows:

$$\text{Min } Z = \sum_{i} \sum_{j} (P_i^a D_j^a + P_i^d D_j^d) X_{ij}$$

S.t.: $$\sum_{j} X_{ij} = 1;\ \forall i; \qquad (2.1)$$

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \leq 1; \forall i, j; \qquad (2.2)$$

$$X_{ij} = 0 \ or \ 1; \forall i, j$$

The cost in the objective function is the walking distance for both arrival and departure passengers. This is based on the fact that for any aircraft occupying the gate there is a certain number of arrival passengers when the aircraft arrives at the gate and a certain number of departure passengers when the aircraft departs from the gate. Thus “flight”, which is *i* in the model, in fact stands for the “flight ground leg”, which includes the arrival of the aircraft at the gate and the departure of the aircraft from the gate.

There are two basic constraints in the model. The first Constraint (2.1) is the "Single Assignment Constraint", which indicates that for each flight there is one and only one gate assigned to it. The second Constraint (2.2) is the "Ground Time Conflict Constraint", which indicates that there should not be more than one aircraft assigned to the same gate if they have overlapping ground time.

In this model, passengers transfer is not considered, which complicates the problem. To avoid excessive computation time, many researchers proposed their work based on this basic model, thus ignoring the transfer passengers. However, for large international hub airports where there is a sizeable portion of transfer passengers, this approximation will lead to a bias of the solution that favors the arrival and departure passengers only.

2.4 Linearized Quadratic Airport Gate Assignment Models

To include the consideration of the transfer passengers, Haghani and Chen (1998) proposed a heuristic to solve the following linearized quadratic IP model for the gate assignment problem:

$$\text{Min } Z = \sum_i \sum_j \sum_r (P_i^a D_j^a + P_i^d D_j^d) X_{ijr} + \sum_i \sum_{i'} \sum_j \sum_{j'} P_{ii'} D_{jj'} Y_{iji'j'}$$

S.t.: $\sum_j X_{ijr} = 1,\ \forall i\ ,\quad r_i^a \le r \le r_i^d\ ;$ (2.3)

$$\sum_i X_{ijr} \le 1, \forall j, r\ ; \qquad (2.4)$$

$$X_{ijr} \le X_{ij(r+1)}, \forall i, j, r_i^a \le r \le r_i^d - 1; \qquad (2.5)$$

$$X_{ijr_i^a} + X_{i'j'r_{i'}^a} - 2Y_{iji'j'} \geq 0, \forall i, i' \neq i, j, j'; \qquad (2.6)$$

$$\sum_j \sum_{j'} Y_{iji'j'} = 1, \forall i, i' \neq i; \qquad (2.7)$$

$$X_{ijr} = 0 \;\; or \;\; 1; \;\; \forall i, j, r;$$

$$Y_{iji'j'} = 0 \;\; or \;\; 1; \forall i, j, i', j';$$

As a major difference from the basic AGAP model by Babi et al. (1984), Haghani and Chen (1998) used X_{ijr} as the decision variable to represent the assignment of a flight to a gate for any time point, which actually will not change the essence of the problem. Besides the first part in the objective function as the total walking distance for arrival and departure passengers, the second part is the summation of the walking distance for transfer passengers.

Constraints (2.3), (2.4) functions as the "Single Assignment Constraint" and the "Ground Time Conflict Constraint" same as the Constraint (2.1), (2.2). As X_{ijr} is used as the variable, Constraint (2.5) is made to make sure that each aircraft must be assigned to the same gate during its apron time. Constraint (2.6), (2.7) altogether give the constraint $Y_{iji'j'} = X_{ijr_i^a} X_{i'j'r_{i'}^a}$. These two constraints are used to linearize the quadratic part $X_{ijr_i^a} X_{i'j'r_{i'}^a}$, which is used to measure the transfer between flights *i* and *i'*.

Haghani and Chen (1998) introduced a heuristic to solve the problem, which is to obtain several sets of feasible solutions and then choose the best one with the minimum walking distance. They used cases of not more than 10 flights and 5 gates to compare the solution quality of their proposed heuristic with that of the optimal solution from the IP model. For large-scale problems, based on the improvements between the initial and final solutions obtained using the proposed heuristic and the performance of the approach in other cases, they concluded that heuristic can provide close-to-optimal solutions to complex AGAP problem.

Suppose m is the number of flights in the schedule, n is the number of gates, T is the number of time intervals, and T_i is the number of time intervals that flight i dwells on the ground. The total number of constraints in the linearized quadratic IP model proposed by Haghani and Chen (1998) is then $\sum_i m \times T_i + n \times T + \sum_i m \times n \times T_i + m \times (m-1) \times n \times n + m \times (m-1)$, while the number of 0-1 variables in the model is $m \times (m-1) \times n \times n + \sum_i m \times n \times T_i$.

However, an alternative way is to model the problem as X_{ij} of the basic model as well. Thus the model could be simplified to the following form:

$$Min\ Z = \sum_i \sum_j (P_i^a D_j^a + P_i^d D_j^d) X_{ij} + \sum_i \sum_{i'} \sum_j \sum_{j'} P_{ii'} D_{jj'} Y_{iji'j'}$$

S.t.: $\sum_j X_{ij} = 1;\ \forall i;$ (2.8)

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \leq 1;\ \forall i, j; \quad (2.9)$$

$$X_{ij} + X_{i'j'} - 2Y_{iji'j'} \geq 0, \forall i, i' \neq i, j, j'; \quad (2.10)$$

$$\sum_{j} \sum_{j'} Y_{iji'j'} = 1, \forall i, i' \neq i; \quad (2.11)$$

$$X_{ij} = 0 \ or \ 1; \ \forall i, j;$$

$$Y_{iji'j'} = 0 \ or \ 1; \ \forall i, j, i', j';$$

Constraints (2.8), (2.9) are exactly the same meaning as Constraints (2.1), (2.2). Constraints (2.10), (2.11), similar with the Constraints (2.6) and (2.7) respectively, altogether make $Y_{iji'j'} = X_{ij} X_{i'j'}$ so as to linearize the quadratic function $X_{ij} X_{i'j'}$. In such a form, the number of decision variables can be greatly reduced and the structure of the model is also improved.

Another form of linearized quadratic AGAP model in literature is proposed by Mangoubi and Mathaisel (1985), in which a big M constant, a sufficiently large number in the constraints, is introduced. The formulations of the constraints are as follows:

$$\sum_{i'} \sum_{j'} Y_{iji'j'} \leq MX_{ij}; \ \forall i, j \quad (2.12)$$

$$\sum_{i} \sum_{j} Y_{iji'j'} \leq MX_{i'j'}; \ \forall i', j' \quad (2.13)$$

$$\sum_{j} \sum_{j'} Y_{iji'j'} = 1; \ \forall i, i' \neq i \quad (2.14)$$

By Constraints (2.12) and (2.13), when any variable X_{ij} or $X_{i'j'}$ equals to 0, $Y_{iji'j'}$ will be 0. Combined with Constraint (2.14), Constraints (2.12) and (2.13) make sure that only when X_{ij} and $X_{i'j'}$ all take the value of 1 will the corresponding $Y_{iji'j'}$ takes the value of 1.

Chapter 3 Extension of the Basic AGAP Model

Topics in this chapter:

Background

Performance Criteria in Practice

Extended IP Modeling for Practical AGAP Problem

Case Study

3.1 Background

Airports face the challenge of satisfying multi-criteria service environment for not only passengers but also ground service providers and airlines. According to the service criteria, different airports have different requirements. With the changing environment such as the increase in the number of flights, expansion of terminals, special requests from airlines etc, the airport needs to have a flexible platform to deal with these changes efficiently and effectively, while copying with the possible future changes. As most of the previous works focus on the passengers' walking distance, we see a limited elaboration in literature on the practical application to take into account the other service criteria of airport, airlines, and ground service providers etc.. Most of the previous works in literature take the passenger walking distance as the only criterion of the optimal aircraft-to-gate assignment. Though Yan and Huo (2001) expanded the discussion to include possible delays of aircrafts, many other practical criteria were not included. As mentioned by Su and Srihari (1993), the most difficult part of the problem is to identify the rules to guide the assignment process, because of the large number of factors which have to be taken into account. There is a necessity to explore the possibility of IP modeling in solving these factors. With the improvement on the IP solution packages, such as CPLEX, it is becoming more efficient to solve the IP problem than before, while obtaining optimality. By investigating into the practical problem in one of the biggest international hub airports in Asia, we tried to explore the efficiency and effectiveness of the IP modeling in solving the AGAP problem that incorporates the important criteria that the airport use in practice to achieve not only feasible flight-to-gate assignment but also to provide more convenience to passengers, to satisfy the requests by airlines, to make the baggage handling process more convenient for ground services providers, to reduce the taxi-way traffic congestion in the airport as to improve many other aspects.

3.2 Performance Criteria in Practice

There are many aspects that the airport authority needs to consider during the gate assignment procedure. According to our analysis at an international hub airport, the performance criteria during the airport gate assignment procedure are much more than those found in the literature. The practical considerations for an airport are:

1) Passenger Walking Distance

To provide passengers with better service, the airport authority needs to minimize the walking distance that passengers have to undertake.

2) Baggage Handling Distance

To facilitate the baggage handling efficiency, the airport authority prefers to reduce the baggage handling distance for the ground service providers.

3) Gate Compatibility

Large aircrafts normally are not allowed to park at a small gate. Also some aircrafts need special services or security checks and are only allowed to park at certain gates.

4) Neighboring of Aircraft

For some gates large aircrafts may not be allowed to be assigned in close neighborhood. For example, the jumbo aircraft B747-400 may not be assigned as a neighbor with another jumbo aircraft B747-400 due to the large wing span of the jumbo aircrafts.

5) Taxi-way Traffic Conflict

This criterion is to make sure that at any time window the number of aircrafts assigned to a taxi-way area should not exceed its traffic capacity.

For an airport, there are some areas that have only one or two taxi-ways. If there are too many aircrafts assigned within this area in a short time window, there will be taxi-way traffic congestion on the apron, since some aircrafts may need to taxi-in and some of them need to taxi-out. This congestion may cause some of the aircrafts having to wait for the taxi-in or taxi-out of other aircrafts. Thus some of the flights may be delayed and the maneuvering will also cause trouble for the airport. To reduce the occurrence of such undesirable situations, this criterion gives each of the different airport taxi-way areas an upper limit on the number of aircrafts to be parked at the same short time period.

6) Airline Non-Adjacency

Flights from some airlines should not be parked near to each other if their ground time overlaps. Such kind of situations is primarily due to security or competition reasons.

7) Aircraft Pushback

If two departure aircrafts are to be pushed back to the taxi-way at the same time or within a small time slot, then they should not be parked as neighbors.

8) Common-Room Gate Usage

One of the important considerations for an airport is the common-room gate constraint. The departure passengers of the flights assigned to the common-room gates will share a common waiting lounge. Thus if an arrival flight is assigned to one of those common-room gates then the other gates cannot allocate any departure flight or there will be a passenger guiding problem because during that time period, there are both arrival passengers and departure passengers in one common area.

9) Critical Transfer Flight

For some of the flights, it would be necessary to park the aircrafts at nearby gates to reduce the transfer walking distance between these two flights. Such flights are called critical transfer flights. As an example, if some flight is delayed and the passengers need to transfer to another flight shortly, it will be necessary for these two transfer aircrafts to be assigned nearby. Airlines prefer such kinds of assignment to make sure that all the critical transfers would be assigned properly. If those critical transfer passengers have to stay at the airport because of not being able to catch the connecting flight due to delayed arrival, the airlines will have to pay for their overnight stay.

10) Terminal Assignment

Some flights must be assigned to their airline’s designated terminal.

11) Airline Limitation on Gate Usage

Some gates can only be used for certain airlines.

12) Gate Night Closure

Flights arriving or departing at night cannot be assigned to a gate that is closed for maintenance during night time.

13) Aircraft Towing

If an aircraft occupies a gate for a long period of time then it will block other aircrafts from using this gate. Such kinds of idle occupancy are also expensive to airlines. An airline would like its aircraft to be towed off a gate if the aircraft occupies a gate for a long period of time, unless it is an over-night stop.

14) Flight Crew and Aircraft Rotation

To let the crew or pilots catch the next connecting flight in a short period of time, such flights are also regarded as critical transfer flights.

According to our observation at an international hub airport, all these criteria are included in the real-life aircraft-to-gate assignment by the airport. Thus we propose here an Extended Basic AGAP Model to incorporate these airport considerations into the IP model.

3.3 Extended IP Modeling for Practical AGAP Problem

3.3.1 Formulation

In this section, we will discuss an extended Basic AGAP Model that is suitable for the airport as well as the practical performance considerations in the airport and their corresponding IP modeling methods. To illustrate the modeling techniques for real problems, we use a weighted Extended Basic AGAP model, where weights are introduced to balance the importance of the objectives in the objective function. In order to take into account the transfer passengers' walking distance as well as the corresponding baggage handling distance without resorting to the usage of a quadratic function, we included the assumption that the passengers as well as the baggage at a gate will be transferred to the other gates equally likely in addition to the assumptions we have in the Basic AGAP Model. The transfer distance for passengers and baggage handling at a gate is then an approximated average distance from the gate to the other gates. The model is as follows:

Min $Z =$

$$\sum_i \sum_j (P_i^a D_j^a + P_i^d D_j^d + P_i^t D_j^t) W_{ij} X_{ij} + \alpha \sum_i \sum_j (P_i^a H_j^a + P_i^d H_j^d + P_i^t H_j^t) W_{ij} X_{ij} + M \sum_i \sum_{j=n+1}^{n+K} P_i X_{ij}$$

S.t: $\sum_j X_{ij} = 1; \ \forall\, i;$ (3.1)

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \le 1; \ \forall\, i, j; \quad (3.2)$$

$$X_{ij} + \sum_{i' \in B_i} \sum_{j' \in N_j} X_{i'j'} \le 1; \ \forall\, i, j; \quad (3.3)$$

$$\sum_{i \in I_{ca}} \sum_{j \in A_a} X_{ij} \le C_a \, ; \; \forall \; a \, ; c; \tag{3.4}$$

$$X_{ij} + \sum_{i' \in I_i} \sum_{j' \in N_j} X_{i'j'} \le 1; \; \forall \, i, \, \mathrm{i'} \in A_i \; ; j; \tag{3.5}$$

$$X_{ij} + \sum_{j' \in N_j} X_{i'j'} \le 1; \; \forall \, i, \, \mathrm{i'} \in DT_i \; ; \tag{3.6}$$

$$\sum_{i' \in DP_i} \sum_{j' \in CM_p} X_{i'j'} + \sum_{j' \in CM_p} X_{ij'} \le 1; \; \forall \, i, \; \forall \, p; \tag{3.7}$$

$$X_{ij} \le \sum_{j' \in NR_j} X_{i'j'} \, ; \; \forall \, i \in CR \; , i' \in CR_i \; , j; \tag{3.8}$$

X_{ij} = 0 or 1; for all the i, j ;

In the objective function the first part is to measure the total passenger walking distance for arrival, departure and transfer passengers. For arrival and departure passengers, the measurement is similar as that stated in the Basic AGAP Model. For the transfer passengers, we introduce D_j^t, the average walking distance for transfer passengers at gate j, to approximate the transfer passengers' walking distance at gate j. It is assumed that the transfer passengers from gate j will transfer to the other gates equally likely. Such an approximation will not take into account the destination gate that passenger may transfer to. In addition, we consider the airlines' parking preferences. It is based on the fact that some airlines would prefer their aircraft to be assigned at certain areas at the airport if the number of available gates within the parking area is enough. They prefer such kinds of assignment so that they could monitor their flights and allocate their personnel more efficiently. Also, because there are normally more than one ground service providers in a large airport that would have contracted airlines to their services, they would like the aircrafts of their contracted airlines to be assigned to gates near their service center area, where most of their equipments and facilities are allocated. To tow all the equipment and facilities far away to another gate to do the aircraft service may not be convenient for the ground service providers. If the aircrafts to be serviced are at nearby gates, the ground service providers may not even need to pack and unpack their facilities, which can greatly improve the efficiency of their work. Thus flights of different airlines prefer to be assigned to different gate areas. W_{ij} is the weight we introduce to the objective function, which equals to 1 if gate *j* is within flight *i*'s airline preferred parking area, and a sufficiently large number otherwise. For those flights with no airlines' parking preferences' W_{ij} will be 1. The reason for us to put this criterion in the objective function instead of introducing a set of constraints to confine the flights of the airline to certain gates is that in reality such criterion is just a preference for the airline but not a hard constraint. If there is no preferred gate available, the airport would park the aircraft at any available gate. Introducing a set of constraints to confine the flights of the airline to certain gates will result in the towing of the aircrafts to the remote stands when there is no preferred gate available, even though there may be other gates available during that time period. Thus, we model such preferences into our objective function, rather than as hard constraints.

The second part of the objective function is the total baggage handling distance. The number of baggage that needs to be dispatched depends on the number of arrival and departure passengers as well as the transfer passengers. Baggage of the arrival passengers will be sent to the baggage sorting center by the ground service provider and then transferred to the baggage claim area for passengers. Baggage of the departure passengers will be sent to the baggage sorting center first before being collected and sent to the departure flight by the baggage handlers. Baggage of the transfer passengers will be sent to the sorting center by the arrival flight's contracted ground baggage handler and later collected and sent to the departure flight by its corresponding contracted ground service provider. Similar with the measurement of the transfer passenger walking distance, the average transfer baggage handling distance is assumed to be related to the position of the gates. The baggage is assumed to be transferred equally likely to other gates. The number of baggage sorting centers may be different for different airports. In the objective function, α is the weight to measure the importance between passengers' walking distance and ground service providers' baggage handling distance. It can be determined by the airport operators themselves. For an airport with baggage connecting problems, α should be made large enough in contrast with the passenger walking distance.

In previous work, researchers mainly model the problem according to the fixed gates in the airport. However, it is possible and frequent for a busy airport to face the problem of not enough available gates during peak hours in a day. In such a case, we will have to assign some of the aircrafts to the remote stands to wait for a gate to be freed up or for a shuttle bus to pick the passengers to the terminal block. Such kind of off-gate events happen during peak hours when there are a lot of flights arriving at the airport within a short time slot. In our modeling, we give associate each of the remote stands from 1 to K with a sufficiently large coefficient M. The model would not select such kind of assignment unless there is no fixed gate possible. Also P_i , which is the total number of passengers on the flight *i*, is introduced here to make sure that those flights assigned to remote stands carry the least number of passengers. Aircrafts with more passengers would be selected to be assigned to a fixed gate to avoid the penalty of big *M* in the coefficients of the objective function. This will minimize the number of passengers facing the inconvenience.

3.3.1 Constraint Illustration:

Constraints (3.1, (3.2) are the same meaning with previous Constraints (2.1) and (2.2) respectively. The other constraints are illustrated as follows:

Constraint (3.3) --- The Neighboring Conflict Constraint:

This constraint is used to avoid large aircrafts being assigned as neighbors because the large wing span of the jumbo aircrafts may affect the parking of other jumbo aircrafts at neighbor gates. For example, in one of the international hub airport we investigated, the jumbo aircraft B747-400 is not allowed to be assigned as a neighbor with another jumbo aircraft B747-400. The constraint will make sure that the number of decision variables that takes a value of 1 corresponding to the assignment at the neighboring gate for jumbo flight will not be more than 1.

Constraint (3.4) --- Taxi-way Traffic Conflict Constraint:

This constraint is to make sure that at any short time window, the number of aircrafts assigned to taxi-way area a should not exceed its traffic capacity C_a to avoid the taxi-way congestion that may cause flight delays and aircraft maneuvering. This constraint gives an upper limit on the number of aircrafts at each of the different airport areas within a short time window.

To model this constraint, we will check all the arrival time of the flights in our planning time horizon. At each of the arrival time point, we will find the corresponding I_{ca}, the flight sets c where more than C_a flights have overlapping ground time. As only these time points are possible for taxi-way congestion, constraints are then introduced according to these.

Constraint (3.5) --- Airline Non-Adjacency Constraint:

This set of constraints is to make sure that flights from some airlines should not be parked near to each other if their ground time overlaps. Here we introduce N_j to represent the set of neighbor gates of gate *j*. To model this set of constraints we will need to check the flights that have overlapping ground time because only such flights would be adjacent to each other in a certain time window.

Constraint (3.6) --- Pushback Constraint:

This constraint is to make sure that aircrafts that depart at the same time should not be parked as neighbors to avoid the possibility of being pushed back to the taxi-way in the same time slot.

Constraint (3.7) --- Common-Room Gate Constraint:

This constraint is to make sure that if an arrival flight is assigned to one of those common-room gates then the other gates cannot allocate any departure flight during certain common-room gate usage time to avoid a passenger guiding problem, whereby during the time period there are both arrival passengers and departure passengers in one common lounge area. The common-room usage time is regulated by the airport authority. According to the practice at one of the international airports, we observe that such a time period is two hours. The constraints are modeled according to each of the common-gate room gate area p .

Constraint (3.8) --- Critical Transfer Constraint:

To assign critical transfer flights to nearby gates to facilitate passengers to catch up the flight at the destination gate we adopt a set of Critical Transfer Constraint to confine those critical transfer flights to nearby gates.

We model the constraint as $X_{ij} \leq \sum_{j' \in NR_j} X_{i'j'}$ so that as long as X_{ij} equals to 1, one of the decision variables $X_{i'j'}$ corresponding to the assignment of the other critical transfer flight will have to be 1 for one of the nearby gates. If X_{ij} takes the value of 0, the corresponding variable of the other critical transfer flight will not be confined to nearby gate assignment.

Such a modeling approach is better than the one that was proposed by Mangoubi and Mathaisel (1985). They proposed the modeling of aircrafts to be assigned to nearby gates in the form as $\sum_{j}\sum_{j'} X_{ij} D_{jj'} X_{i'j'} \le D_{ii'}^{\max}$, where $D_{jj'}$ is the walking distance from gate *j* to gate *j'* and $D_{ii'}^{\max}$ is the maximum allowable transfer walking distance between flight *i* and *i'*. They mentioned in their work that this constraint is nonlinear and undesirable and thus proposed a post-optimal method to deal with such a constraint by forcing one decision variable X_{ij} to be 1 and seeking the corresponding solution with the constraint $\sum_{j'} D_{jj'} X_{i'j'} \le D_{ii'}^{\max}$. However, they mentioned that even this method is only suitable when flights *i* and *i'* serve the same large number of transfer passengers. For general situations that a group of passengers comprise the majority of passengers in two or more flights, they claim that the airport should adopt the appropriate solution depending on the situation at hand. In contrast, our model can solve the general nearby gate assignment for flights without resorting to any post-optimal solution method.

In practical crew and aircraft rotation problems, the solution to let the crew or pilots catch the next connecting flight on duty in a short period of time is to regard such kind of flights as critical transfer flights. The modeling of critical transfer flights is the same as above.

3.3.2. Additional Criteria

There are some other important considerations at an airport. We call such kind of constraints ‘Unary Constraints’ because they are related with how to process some variables instead of making constraint functions. For the unary constraints, since it is possible to remove the corresponding variables in the model besides forcing them to be 0, we did not include such constraints in the above model. However, the unary constraints are important for proper modeling of the real-life problem. The unary constraints and their corresponding modeling are as follows:

1) Gate Compatibility Constraint:

This constraint is to make sure that if the aircraft of flight *i* is not compatible with gate *j*, then we will not assign it to gate *j*. Big aircrafts normally are not allowed to park at a small gate. Also aircrafts that need special service or security check are only allowed to park at certain gates.

Modeling: All the relevant variables X_{ij} are deleted or forced to be 0 if the aircraft of flight *i* is not compatible with gate *j*.

2) Unknown Aircraft Type:

In practice, if some flight *i*'s aircraft type is unknown, then it will be assigned to a remote stand.

Modeling: All the relevant variables X_{ij} are deleted or forced to be 0 for unknown aircraft *i*, for all fixed gates *j*.

3) Same Terminal:

Flight *i* belonging to some airline must be assigned to the airline's designated terminal.

Modeling: All the relevant variables X_{ij} are deleted or forced to 0 if flight *i* belongs to some airline but gate *j* is not in the airline's designated terminal.

4) Airline Limitation:

Some gates can only be used for certain airlines.

Modeling: All the relevant variables X_{ij} are deleted or forced to 0 if gate j is not designated for the airline of flight *i*.

5) Training Flight:

If a flight is a training flight with night stopping, we will assign it to a remote stand.

Modeling: Before running the model, we check all such kind of flights and assign them to remote stands. They will not be generated as variables in our model.

6) VIP Flight:

If flight *i* is a VIP flight, we will assign it to a gate with VIP facilities.

Modeling: If flight *i* is a VIP flight then all the relevant variable X_{ij} are deleted or forced to 0 if gate *j* does not have VIP facilities.

7) Night Closure:

If flight *i* arrives or departs at night, then it cannot be assigned to a gate closed during night time.

Modeling: Before running the model, we can check which gates are not available, as well as their corresponding unavailable time periods. All the flights will not be assigned to those gates during their unavailable time periods by deleting the corresponding decision variables.

8) Aircraft Towing:

If an aircraft occupies a gate for a long period of time, it will block other aircrafts from using this gate. Such kinds of idle occupancy are also expensive to airlines. An airline would like its aircrafts to be towed off a gate if the aircraft occupies a gate for a long period of time, unless it is an over-night stop.

In our model, we will do a preprocessing to check the arrival time and departure time of each flight. A flight with a ground dwelling time more than a certain time limit defined by the airport will be split into two flight legs. Decision variables will then be generated based on each of the flight legs.

3.4 Case Study

To test and compare the models we have introduced, we use the actual daily flight schedule and gate information at an international hub airport. There are 172 flights to be assigned to 34 gates on a particular day. In addition, there are 8 gate maintenance tasks on that day. For all the gate maintenance tasks on that day, we generated them as special decision variables, which are set to be 1 from the starting time to the ending time of the maintenance.

For the constraints in the basic AGAP model, we included the basic considerations, such as passenger walking distance, ground time conflict constraints, gate compatibility constraints etc. The solution of this model is to give an illustration on the efficiency of solving the real problem through the IP model. We did not incorporate the baggage handling criterion in the experiment because it will not change the structure of the model but only the cost coefficients and this will not affect the computational efficiency. Also, we did not incorporate other criteria in the experiment since the number of constraints related with criteria such as the VIP flight assignment, and critical transfer flight constraint is much less when compared with the number of the two basic constraints: Ground Time Conflict Constraint and Single Assignment Constraint. In fact, among the daily hundred flights, only a few flights are VIP or critical flights. Transfer passengers' walking distance consideration is not included in the current airport system. To make the IP solution comparable with the current solution, we did not include this consideration in the model. We have run the experiment of a one-day 24hrs gate assignment planning problem for all the airlines at one of the terminals in an airport on a particular day, considering Single assignment constraints, Ground time conflict constraints, Gate compatibility constraints and Aircraft towing altogether. The detailed input data structuring is attached in Appendix I.

In the model for the real problem, there are 6120 decision variables. The number of constraints in our model is 7217, not including the binary property constraints. We used CPLEX 7.5 to solve the model under Windows XP using a Pentium III 866MHz CPU, 256M RAM PC. This 0-1 IP Model can be read in 0.23 second. Using MIP OPTIMIZER, CPLEX can solve the problem in 32.23 seconds after 2578 iterations. The minimal total walking distance for all the arrival and departure passengers is 50989000 meters. CPLEX MIP Pre-solve eliminated 4971 rows and 1161 columns. The reduced MIP has 2246 rows, 4755 columns, and an optimal solution was found. The passenger walking distance is 13.40% less than the current solution at the airport, which uses a constraint programming to solve the problem.

To further test the solution under different scenarios of the arrival and departure passenger numbers, we repeated the experiment by randomly generating passenger numbers to compare the solutions of the IP model. With the flight-to-gate assignment of the current system we recalculate the total passenger walking distance solution of the current system based on the randomly generated arrival and departure passenger numbers. For the IP approach, the solutions are achieved through the resolving of the model. According to the six random cases we have run, the IP model on average gives a solution that is 13.90% reduction of the total passenger walking distance than that of the current system. The results are shown below, where the last column is the reduction of the total passenger walking distance in percentage when compared with current solution:

Table 3.1 IP Optimal Solution of the Basic AGAP Model in comparison with the current airport solution

Model Type	Problem Size		Solution to Current Flight-to-gate Assignment	IP Optimal Solution	Improvement	Percentage
	No. of Flights	No. of Gates				
Basic AGAP Model	172	34	61262122.50	52918221.42	8343901.08	13.62%
			60843721.90	52307347.72	8536374.18	14.03%
			61273397.40	52756395.16	8517002.24	13.90%
			61415410.30	53136612.99	8278797.31	13.48%
			61027421.40	52245575.46	8781845.94	14.39%
			60516676.30	52068548.29	8448128.01	13.96%
Average						13.90%

Chapter 4 MIP Modeling for AGAP Problem

Topics in this chapter:

The Converted Linearized quadratic AGAP Model

The 3-terminal AGAP IP Model

The Multi-terminal AGAP IP Model

Extension to Multi-pier AGAP Model

Comparison Experiments

4.1 The New Converted Linearized Quadratic AGAP Model

4.1.1 Introduction

As stated in previous Chapter 2, there are two major works in the linearized quadratic modeling of the problem: the Linearized Quadratic IP AGAP Models proposed by Mangoubi and Mathaisel (1985) and Haghani and Chen (1998). However, both works concluded that the computational time for solving an even small problem using their proposed linearized quadratic models without resorting to any heuristic methodology is unreasonably large, as stated in their case studies. Though better efficiency can be achieved through using other methodologies such as a heuristic approach, we tried to find a better way of modeling the problem to improve the mathematic structure of the model, which in turn greatly improves the efficiency of the solution process without resorting to other solution methodologies. The advantage of such improvement of the modeling structure is that the optimality of the solution will be exactly the same but the solution time is greatly reduced.

4.1.2 The Model

Our proposed new linearized quadratic model is as follows:

$$\text{Min } Z = \sum_{i} \sum_{j} (P_i^a D_j^a + P_i^d D_j^d) X_{ij} + \sum_{i} \sum_{i'} \sum_{j} \sum_{j'} P_{ii'} D_{jj'} Y_{iji'j'}$$

S.t.: $\sum_{j} X_{ij} = 1;\ \forall i;$ (4.1)

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \le 1;\ \forall i, j; \quad (4.2)$$

$$Y_{iji'j'} \geq X_{ij} + X_{i'j'} - 1; \forall i, i' \neq i, j, j'; \quad (4.3)$$

$$Y_{iji'j'} \geq 0; \forall i, i' \neq i, j, j'; \quad (4.4)$$

$$X_{ij} = 0 \text{ or } 1; \forall i, j$$

4.1.3 Illustration to the New Converted Linearized Quadratic AGAP Model

In the proposed model, Constraints (4.1), (4.2) are of the same meaning as previous Constraints (2.1), (2.2). Through the simplification of the constraints, we can improve the structure of the model. We can see that as the essence of this model is minimization, the variables $Y_{iji'j'}$ will always take its lower bound. Thus in Constraint (4.3), when X_{ij} and $X_{i'j'}$ both take the value of 1, $Y_{iji'j'}$ will be 1. When only one of the X_{ij} and $X_{i'j'}$ takes the value of 1, the lower bound of $Y_{iji'j'}$ will be 0. However, when X_{ij} and $X_{i'j'}$ are both 0, Constraint (4.4) will make sure that the lower bound of $Y_{iji'j'}$ will be 0. Besides the simplification of the structure of the constraints, we can see that instead of being restricted be to binary variables, $Y_{iji'j'}$ is set as free variables, which makes the model simplified compared with the previous works. The improvement of the structure and the less restriction to the variables in turn will reduce the solution time for the problem significantly, which has been verified in our experiment runs.

4.2 The 3-terminal AGAP IP Model:

4.2.1 Introduction

According to the statistics of the international hub airports, a great portion of the passengers are transfer passengers. If we do not consider transfer passengers, the assignment solution will lead to a bias which favors only arrival and departure passengers. However, incorporating the transfer passengers into the model by linearizing the quadratic part makes the model greatly expanded and difficult to be solved in reasonable time. As the previous work on IP modeling has been proven to be time-consuming to solve the problem when the transfer passengers are considered, we introduce an alternative approximation approach to model the problem to improve the efficiency.

In real practice, there are usually several terminals for a large airport. Most of the transfer is within one terminal, which usually is within reasonable walking distance. However, there are certain situations that passengers have to walk all the way and take a shuttle bus or train to transfer to another terminal for boarding on another flight. In such a case, the walking distance and the inconvenience for the passengers are much greater than the case of within-terminal transfer. To minimize the cross-terminal walking distance for transfer passengers is important for airport.

The number of terminals does not exceed three for many large airport we will first introduce a 3-terminal Airport Gate Assignment Model to minimize the cross-terminal transfer as well as the total passenger walking distance for arrival and departure passengers. This model is designed for any 3-terminal airport. The layout of the terminals is not restricted to any certain type. It can be linear, looped or have other layout types. The layout and the relative cross-terminal walking distances of the 3-terminal Model can be described as follows and we will later extend our discussion to multi-terminal airport layout:

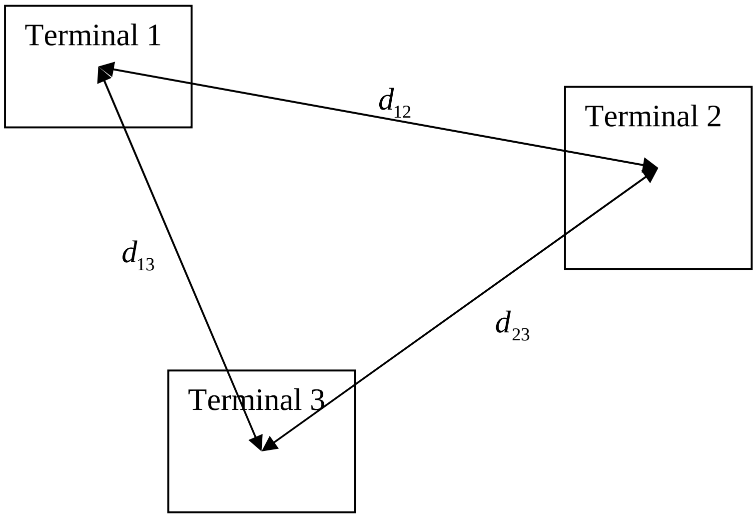


Figure 4.1 3-terminal Airport Layout

4.2.2 The Model

The 3-terminal Airport Gate Assignment Model we proposed is as follows:

$$\text{Min } Z = \sum_i \sum_j (P_i^a D_j^a + P_i^d D_j^d) X_{ij} + \sum_i \sum_{i'} P_{ii'} \ y_{ii'}$$

S.t: $\sum_j X_{ij} = 1 ; \ \forall i;$ (4.5)

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \le 1 ; \ \forall i, j; \quad (4.6)$$

$$l_i^e = \sum_{j \in T_e} X_{ij} \ ; \ \forall i , e; \quad (4.7)$$

$$y^e_{ii'} \geq l^e_i - l^e_{i'}\,; \quad \forall\, i,\, i' \neq i,\, e;\ (e{=}1,2,3) \tag{4.8}$$

$$y^e_{ii'} \geq l^e_{i'} - l^e_i\,; \ \forall\, i,\, i' \neq i,\, e\ ; \tag{4.9}$$

$$y_{ii'} \geq d_1\, y^1_{ii'} + d_2\, y^2_{ii'} + d_3\, y^3_{ii'} \ ; \ \forall\, i,\, i' \neq i; \tag{4.10}$$

$$X_{ij} = 0 \text{ or } 1;\ \forall\, i,\, j;$$

4.2.3 Illustration to 3-terminal AGAP Model

1) Objective Description:

Our objective is to minimize the walking distance for arrival and departure passengers as well as to minimize the cross-terminal transfer walking distance. The first part of the objective function is the walking distance of both the arrival and departure passengers. The second part is the cross-terminal walking distance of transfer passengers from flight i to i'. If the transfer is within one terminal, this distance is zero. If i and i' are assigned to different terminals then the transfer walking distance is the distance between the centers of the two different terminals. Here, the cross-terminal transfer distance is assumed to be the distance between the two terminals plus the average walking distance within one terminal. Because the distance between terminals is normally much bigger than the walking distance within one terminal, we did not take an exact measurement of the transfer distance from the originating gate to the destination gate but the approximation of it. As our model is to minimize cross-terminal transfer, this objective function would be enough to measure such kinds of transfer instead of the exact gate-to-gate transfer walking distance.

2) Constraint Illustration:

Now we will illustrate the function of the constraints. The constraints (4.5) and (4.6) are the Single Assignment Constraint and the Ground Time Conflict Constraint respectively the same as those constraints illustrated in Chapter 2. Constraints (4.7) to (4.10) altogether make a measurement of the cross-terminal transfer distance from flight *i* to flight *i'*. If the transfer pattern is within one terminal then the cross-terminal transfer walking distance is $y_{ii'}$ which will be 0. If the transfer for *i* and *i'* is cross-terminal transfer then $y_{ii'}$ will take the value of the distance between the terminals that assigned with *i* and *i'*. The cross-terminal distance is thus the value of $y_{ii'}$.

In Constraint (4.7) we define $l_i^e = \sum_{j \in T_e} X_{ij}$. Because any flight *i* will be assigned to only one gate at some terminal, for all the l_i^e, i.e., l_i^1, l_i^2, l_i^3, only one of them will be 1. With Constraints (4.7), (4.8) and (4.9), $y_{ii'}^e$ can be used to define the transfer pattern. If flights *i* and *i'* are assigned to different terminals, $y_{ii'}^e$ will take a value of 1, 0 otherwise.

By defining $d_1 = \frac{(d_{12} + d_{13} - d_{23})}{2}$, $d_2 = \frac{(d_{12} + d_{23} - d_{13})}{2}$ and $d_3 = \frac{(d_{13} + d_{23} - d_{12})}{2}$, where d_{12}, d_{23}, d_{13} are the distances between terminals 1 and 2, 2 and 3, 1 and 3 respectively, we can make sure that the $y_{ii'}$ in Constraint (4.10) is the cross-terminal transfer distance for *i* and *i'*. This can be seen from the following table 4.1. Moreover, the sense of the objective function is to minimize and we can see that $y_{ii'}$ actually would take the smallest value, i.e., to take the equality value in Constraint (4.10). From the following table we can find that for any assignment of transfer flights (i, i') to terminals, the $y_{ii'}$ equals to the cross-terminal transfer distance for i and i'.

Table 4.1 Transfer patterns and the corresponding variable values

Terminal(s) assigned to flights (*i*, *i'*)	**(1,3)**	**(1,2)**	**(2,3)**	**(2,1)**	**(3,2)**	**(3,1)**	**(1,1), (2,2), (3,3)**
$l_i^1 - l_{i'}^1$	1	1	0	-1	0	-1	0
$l_i^2 - l_{i'}^2$	0	-1	1	1	-1	0	0
$l_i^3 - l_{i'}^3$	-1	0	-1	0	1	1	0
$y_{ii'}^1$	1	1	0	1	0	1	0
$y_{ii'}^2$	0	1	1	1	1	0	0
$y_{ii'}^3$	1	0	1	0	1	1	0
$y_{ii'} = d_1 y_{ii'}^1 + d_2 y_{ii'}^2 + d_3 y_{ii'}^3$	d_{13}	d_{12}	d_{23}	d_{12}	d_{23}	d_{13}	0
Transfer Pattern	T1 $\Leftrightarrow$ T3	T1 $\Leftrightarrow$ T2	T2 $\Leftrightarrow$ T3	T1 $\Leftrightarrow$ T2	T3 $\Leftrightarrow$ T2	T3 $\Leftrightarrow$ T1	Within One Terminal
Transfer Distance	d_{13}	d_{12}	d_{23}	d_{12}	d_{23}	d_{13}	0

4.3 The Multi-terminal AGAP IP Model

4.3.1 Introduction

Because the 3-terminal model will be suitable to a limited number of airports, we extended it to the general multi-terminal airport. For a multi-terminal airport, it could have many possible layouts. Here we only investigate on those airports whose terminals are linearly linked, i.e., there is no shortcut from one terminal to another, so that passengers may have to pass through nearer terminal before getting to the further one. The 3-terminal case is different with this in that passengers can get to any other terminal directly. An example of the terminal layout could be illustrated as the following, where we can see that there is no shortcut from terminal 1 to terminal 3 without passing through terminal 2.

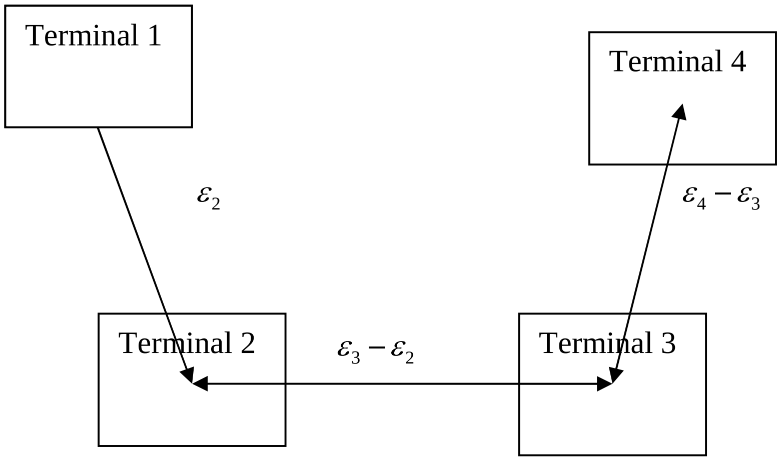


Figure 4.2 Multi-terminal Airport Layout

4.3.2 The Model

The Multi-terminal AGAP Model we proposed is as follows:

$$\text{Min } Z = \sum_i \sum_j (P_i^a D_j^a + P_i^d D_j^d) X_{ij} + \sum_i \sum_{i'} P_{ii'} \; y_{ii'}$$

S.t: $$\sum_j X_{ij} = 1; \ \forall \ i; \tag{4.11}$$

$$\sum_{i' \in I_i} X_{i'j} + X_{ij} \le 1; \ \forall \ i, \ j; \tag{4.12}$$

$$l_i^e = \sum_{j \in T_e} X_{ij} \ ; \ \forall \ i, e; \tag{4.13}$$

$$y_{ii'}{}^e = l_i^e - l_{i'}^e; \ \forall \ i, \ i' \ne i, e = 2, 3, \ldots, E \tag{4.14}$$

$$y_{ii'} \ge \sum_{e=2}^{E} \varepsilon_e y_{ii'}^e \ ; \ \forall \ i, i' \ne i; \tag{4.15}$$

$$y_{ii'} \ge -\sum_{e=2}^{E} \varepsilon_e y_{ii'}^e \ ; \ \forall \ i, \ i' \ne i; \tag{4.16}$$

$$X_{ij} = 0 \text{ or } 1; \ \forall \ i, \ j;$$

4.3.3 Illustration to Multi-terminal Model

1) Objective Description:

The objective in the model is similar with the one in the 3-terminal model. Our objective is to minimize the walking distance for both arrival and departure passengers while minimizing the cross-terminal transfer walking distance as well.

2) Constraint Illustration:

In this model, the objective function and Constraints (4.11), (4.12), (4.13) are of the same meaning with the corresponding constraints in the 3-terminal model. Here, the variable $y_{ii'}$ will take the value of the cross-terminal transfer walking distance based on whether the transfer is cross-terminal transfer or within-terminal transfer. This is defined by the following three constraints:

$$y_{ii'}{}^{e} = l_i^e - l_{i'}^e \; ; \;\; \forall\, i,\, i' \neq \mathrm{i},\, e = 2,3,\ldots,E \tag{4.14}$$

$$y_{ii'} \geq \sum_{e=2}^{E} \varepsilon_e y_{ii'}^e \; ; \; \forall\, i,\, i' \neq i; \tag{4.15}$$

$$y_{ii'} \geq -\sum_{e=2}^{E} \varepsilon_e y_{ii'}^e \; ; \; \forall\, i,\, i' \neq i; \tag{4.16}$$

For example, if flight *i* is assigned to terminal 3 and flight *i'* is assigned to terminal 5, the actual transfer walking distance will be valued as $\left| \; \varepsilon_5 - \varepsilon_3 \; \right|$. This transfer walking distance is much bigger than that within the terminals and so we do not take the transfer walking distance within the terminals here. Also as this model is to minimize the cross-terminal transfers this distance would be sufficient for us to measure the transfer.

4.4 Comparison Experiments

4.4.1 Model Comparison

Compared with the Linearized Quadratic AGAP Model, the numbers of both constraints and variables in our Multi-terminal Gate Assignment Model are much smaller.

Here we will make a comparison of the Multi-terminal AGAP Models with the linearized quadratic model proposed by Haghani and Chen (1998). As the variables $y_{ii'}^{e}$ and l_i^e in the Multi-terminal AGAP Model are for better illustration of the model and they are exactly determined by the value of the variable X_{ij}, the number of variables in the multi-terminal model is actually $m \times n + m(m-1)$ for variables X_{ij} and $y_{ii'}$, where m is the number of flights in the schedule and n is the number of gates. Taking E as the number of terminals in the airport, the number of constraints is $m + m \times n + m \times E + m(m-1)E + m(m-1) + m(m-1)$.

In our modeling of the Constraints (4.14), (4.15) and (4.16) in the Multi-terminal AGAP Model, we only need to model for those transfer flight pairs with $P_{ii'}$ not equal to 0. We define the number of transfer flight pairs with $P_{ii'}$ not equal to 0 to be N^T. Then the number of constraints is: $m + m \times n + m \times E + N^T E + N^T + N^T = m(n + E + 1) + N^T (E + 2)$.

However, for the simplified linearized quadratic IP model proposed by Haghani and Chen (1998), the number of variables is $m \times n + m(m-1)n^2$ and the number of constraints is *m+mn+m(m-1)nn+m(m-1)*. Similarly we can take N^T to calculate the number of effective constraints. The number of constraints for the linearized quadratic model is thus $m+mn+N^T n^2+N^T = m(n+1)+N^T(n^2+1)$

The comparison of the numbers of constraints and variables of the Linearized Quadratic AGAP Model and our model is as shown in the following table:

Table 4.2 Comparison of the Linearized Quadratic AGAP Model and the Multi-terminal AGAP Model

	No. of Variables	***No. of Constraints***
Linearized Quadratic AGAP Model	$m \times n + m(m-1)n^2$	$m(n+1)+N^T(n^2+1)$
Multi-terminal AGAP Model	$m \times n + m(m-1)$	$m(n+E+1)+N^T(E+2)$

We can see that the numbers of both constraints and variables are much smaller in the proposed multi-terminal model than that in the pervious linearized quadratic model.

4.4.2 Experiment Scenario

To extend our discussion of the AGAP problem to include the transfer passenger consideration, we compare the linearized quadratic models by Haghani and Chen (1998) and Mangoubi and Mathaisel (1985) with our proposed New Linearized Quadratic Model and the Multi-terminal Model. To make the comparison consistent, the experiment is run under the same scenarios. However, as the solving for the linearized quadratic model is time-consuming even for small problems, we designed the experiment with a problem size that the linearized quadratic model can be solved in reasonable time. Based on this, we designed the experiment size to be 8 flights with 6 gates. In addition, because this test case is not from the actual airport schedule as in the previous one, we have considered several parameters that may affect the results. We try to incorporate more possibilities to see whether the variation of the parameters will greatly affect the solutions, so as to capture the results more precisely.

In our experiment, we have 3 sets of parameters to cover the possible combinations of the situations that may affect the solution in practice. They are:

I) The percentage of the transfer passengers;

II) The transfer pattern;

III) The cross-terminal walking distance;

The detailed data of the experiment parameter design can be referred in Appendix II.

4.4.3 Computational Results

1) Solution Quality:

The solutions for the 16 cases taking into account cross-terminal walking distance, percentage of transfer passengers and the transfer patterns are shown in the following table. The solution unit is in meters. In the last column, we indicated the percentage of the difference of the solutions.

For the multi-terminal model, we did not use the objective value to measure the total passenger walking distance but to calculate the total passenger walking distance according to the aircraft-to-gate assignment solution so as to compare with the exact walking distance of the Linearized Quadratic Model.

Table 4.3 Multi-terminal AGAP Model solution in comparison with that of the Linearized Quadratic Model

No.	Cross-Terminal Walking Distance	Percentage of Transfer Passengers	Transfer Pattern*	Linearized Quadratic Model Objective Value	Multi-terminal Model Objective Value	Difference%
1	100	5%	(1)	104840	104840	0.00%
2			(2)	103010	103010	0.00%
3			(3)	102880	102880	0.00%
4			(4)	103010	103010	0.00%
5		15%	(1)	120015	120015	0.00%
6			(2)	111240	111240	0.00%
7			(3)	70635	70635	0.00%
8			(4)	110855	110855	0.00%
9	30	5%	(1)	98330	98330	0.00%
10			(2)	97550	97550	0.00%
11			(3)	97420	97420	0.00%
12			(4)	97550	97550	0.00%
13		15%	(1)	100975	101985	0.99%
14			(2)	98825	98825	0.00%
15			(3)	59855	60770	1.51%
16			(4)	98825	98825	0.00%

** (1) A flight transfers to all the other flights that are possible for its transfer;*

(2) A flight transfers to the nearest departure flight that is possible for its transfer;

(3) A flight transfers to the longest departure flight that is possible for its transfer;

(4) A flight transfers to the median departure flight that is possible for its transfer;

2) Computational Time:

The solution time for the 16 cases using different models is as shown below. The Linearized Quadratic Model is that proposed by Haghani and Chen (1998) in the literature. We compare it with our proposed Multi-terminal Model and the proposed New Linearized Quadratic Model to see the efficiency improvement. The unit for CPU solution time is in seconds. The computer hardware and software conditions are the same as that stated in the experiment of the Basic AGAP Model. The detailed experiment design is shown in Appendix II.

Table 4.4 Multi-terminal Model and New Linearized Quadratic Model computational time in comparison with the Linearized Quadratic Model by Haghani and Chen(1998)

No.	Cross-Terminal Walking Distance	Percentage of Transfer Passengers	Transfer Pattern*	Solution Time (second)		
				Linearized Quadratic Model by Haghani and Chen (1998)	New Linearized Quadratic Model	Multi-terminal Model
1	100	5%	(1)	3818.47	10.9	0.29
2			(2)	4494.47	0.19	0.09
3			(3)	3123.58	0.14	0.21
4			(4)	4760.90	0.35	0.12
5		15%	(1)	7200.22	42.27	0.33
6			(2)	3403.80	0.21	0.11
7			(3)	4897.59	0.34	0.13
8			(4)	5960.39	0.56	0.12
9	30	5%	(1)	3165.96	4.54	0.17
10			(2)	2344.11	0.24	0.10
11			(3)	1156.98	0.26	0.09
12			(4)	2324.24	0.34	0.09
13		15%	(1)	4062.71	16.81	0.10
14			(2)	2887.92	0.21	0.09
15			(3)	2764.89	0.19	0.16
16			(4)	3619.78	0.38	0.21
Average				3749.13	0.15	4.87
Ratio of Average Computational Time of the Model by Haghani and Chen (1998) to the Proposed Model					24994.2	769.84

3) Conclusions:

Under the experiment scenario that we have defined, the Multi-terminal AGAP Model, a proposed model to take into account the transfer passenger walking distance, achieved the optimal solution of the linearized quadratic model in all the cases when the cross-terminal transfer walking distance is relatively large, i.e., 100. However, when the cross-terminal transfer walking distance is much shorter, such as 30, slight solution differences can be seen. This is consistent with the objective of the model to minimize the cross-terminal transfer. From this, we can see that our model is more suitable for airports with long cross-terminal transfer walking distance. Because of the constraint of the great computational time of the linearized quadratic model, we are not able to compare larger cases to indicate the difference with the exact solution. However, from the results in the cases that we have run, the maximum difference is 1.51%. The Multi-terminal AGAP Model can be introduced as a good approximation for the gate assignment problem for multi-terminal airports.

In summary, to compare the efficiency of the proposed Multi-terminal Model and the New Linearized Quadratic Model with the models in literature which also consider transfer passengers, we introduced the work by Haghani and Chen (1998). From the experiment results, the proposed Multi-terminal Model and the New Linearized Quadratic Model give a much more efficient solution than that of Haghani and Chen (1998). In comparison with the Linearized Quadratic Model by Haghani and Chen (1998), the average computational time for the Multi-terminal Model is 24994.2 times faster, and that for the proposed New Linearized Quadratic Model is 769.84 times faster. The heuristic proposed by Haghani and Chen (1998), in comparison, is only 300 times time-saving than the linearized quadratic model. However, as the computer environment and the CPLEX version we have used are different, we cannot compare the exact differences of the efficiency of their proposed heuristic and our proposed models. But the conclusion that the proposed models are much more efficient than the linearized quadratic model in the literature can be confirmed through the experiment results in this section.

4.5 Extension to Multi-pier AGAP Model

4.5.1 Background

In the work of Neufville and Rusconi-Clerici (1978), the authors made a conclusion that when the percentage of transfers exceeds 30%, a pier-finger terminal configuration is better than a linear terminal configuration as the average passengers walking distance would be shorter for the pier-finger terminal configuration. According to the statistics of worldwide international airports, 37% of the airports adopt the multi-pier concept. As the gate assignment model should consider the optimization of the transfers and the model should be able to be solved in practice within reasonable time, we adopted the concept of cross-pier transfer and extend the Multi-terminal AGAP Model to the Multi-pier AGAP Model.

A multi-pier configuration is the airport layout consisting of two or more piers in the airport extended from the terminal block. The piers are linearly aligned along the concourse through which passengers go from one pier to another. There are two types of pier-finger terminals: Centralized pier-finger terminal and semi-centralized pier-finger terminal, based on whether the operation of the piers is centralized or separated as described in the work of Bandara and Wirasinghe (1992). Semi-centralized pier-finger concept is not frequently seen in practice and thus we only investigate on the centralized pier-finger terminal concept here. For an international airport where the passenger check-in procedures and baggage claim operations are centralized in one terminal block, we call it a centralized terminal concept. The following are some examples of the multi-pier terminal concepts:

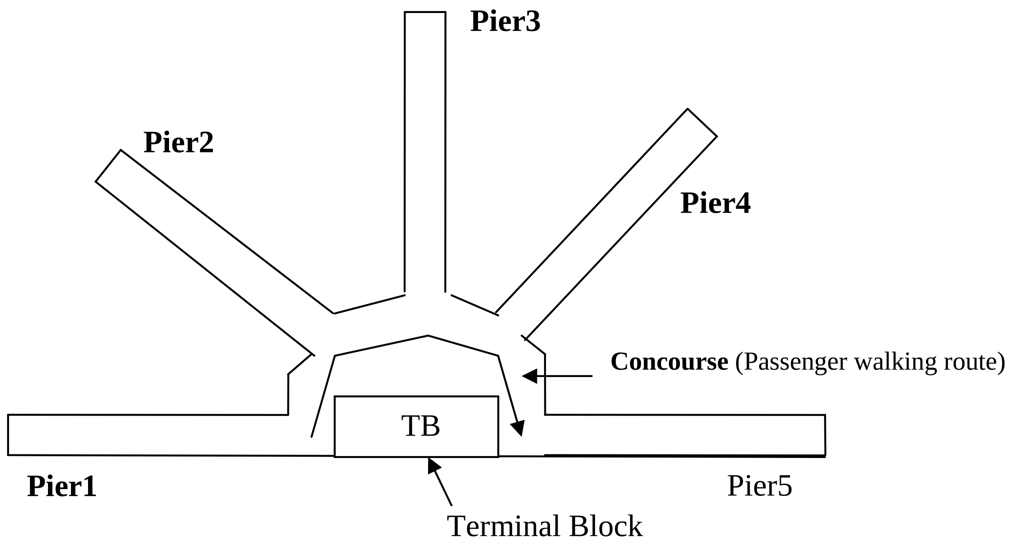


Figure 4.3 Multi-pier terminal concept I: Radial Pier Terminal

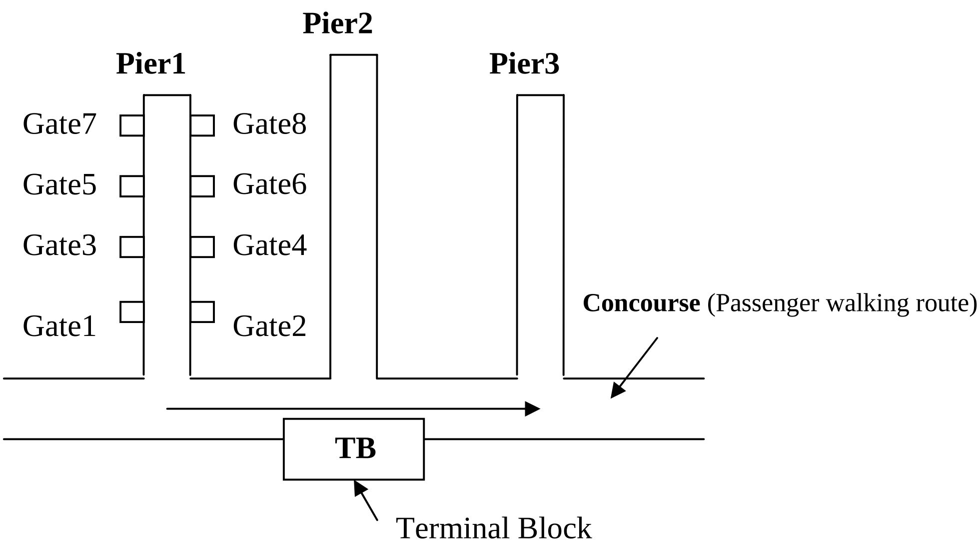


Figure 4.4 Multi-pier terminal concept II: Parallel Pier Terminal

As shown above, each pier has a group of gates. These piers are connected through the concourse. Passengers may go through the concourse to get to the gate at another pier for transfer. For the radial pier terminal, transfer passengers will have to pass by the piers 2 and 3 before arriving at pier 4 from pier 1 because the center part is the terminal block. The terminal block is used for check-in of departure passengers and baggage claim for arrival passengers. There are also some customs facilities in this area and transfer passengers may not go through these facilities to get to pier 4 from pier 1 without passing by pier 2 and pier 3. The walking distance from pier 1 to pier 4 can be approximated as the summation of the distance from pier 1 to pier 2 and pier 2 to pier 3 and so on. This is also true for the parallel multi-pier terminal configuration.

A transfer passenger arriving from a gate at some pier may transfer to the destination gate at the same pier or at another pier. However, passengers would prefer the destination gate to be assigned to the same pier because in this way, passengers can get to know the position of the destination gate easier, though it is possible for the destination gate to be assigned to some nearer gate at another pier. If the destination gate is assigned to another pier, passengers may have to look for the location of the pier first before finding the destination gate, which will be troublesome for passengers who are not familiar with the airport. This can be illustrated by the following figure to indicate how many "passenger direction information" signs are needed to guide a passenger arriving from one gate to transfer to a gate at another pier.

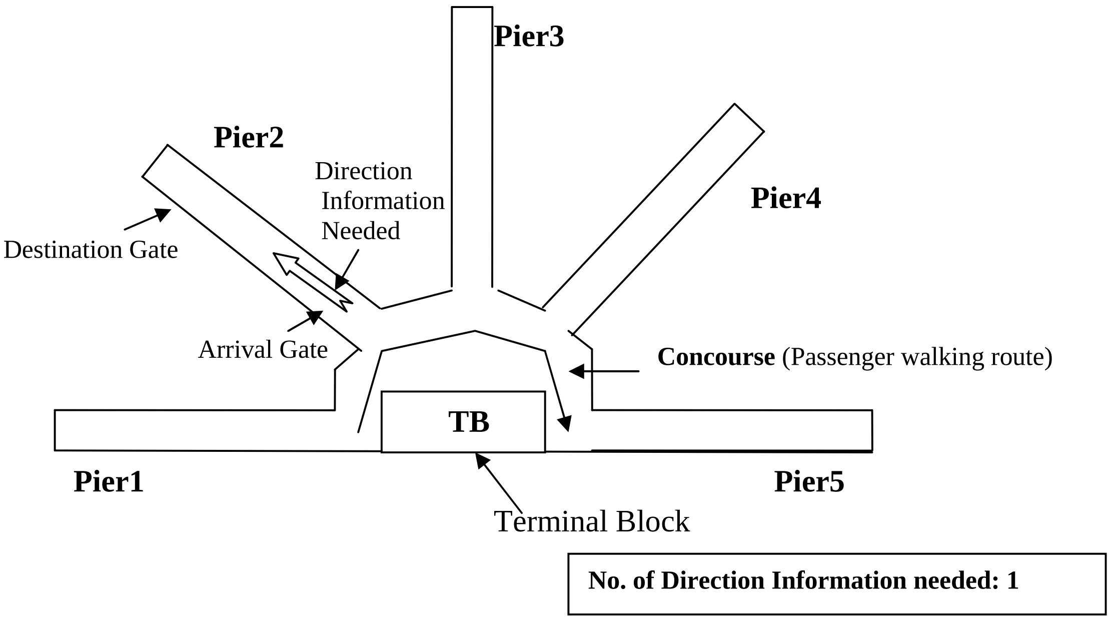


Figure 4.5 Direction Information Needed for the Same-pier Transfer

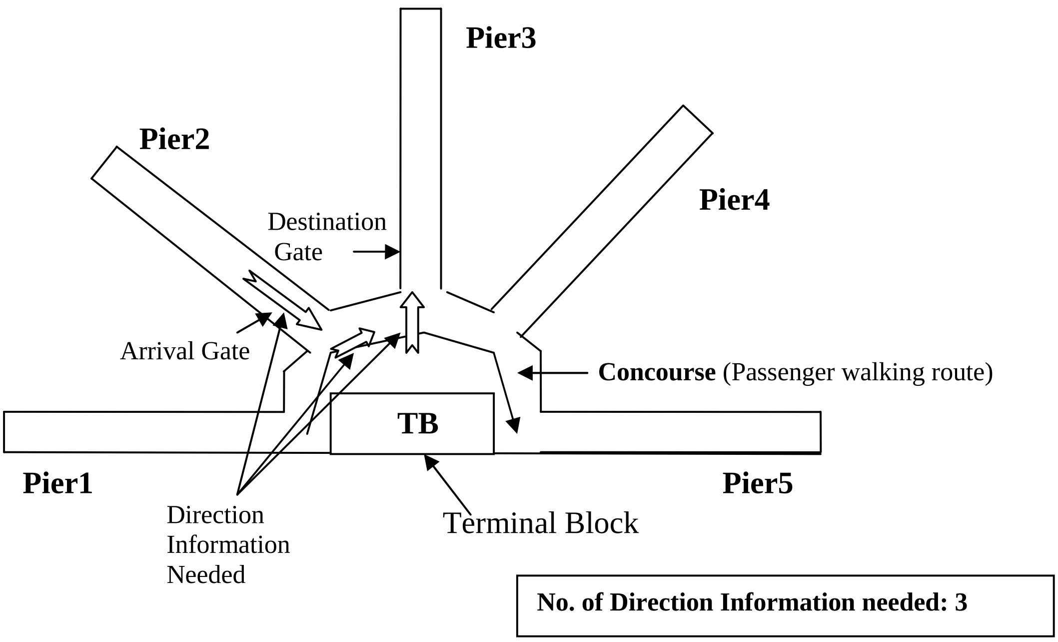


Figure 4.6 Direction Information Needed for Cross-pier Transfer

From the figures above, we can see that passengers would need to find at least three "direction information" signs if they are to transfer to a different pier. However, if their destination gate is at the same pier, i.e., the same gate group, then they only need one direction information sign. Transfer passengers may not be familiar with the location of the gates at the airport and so they would like their destination gate to be assigned to the same pier which is easier to find, than to assign it to a different pier even though the walking distance may be smaller. In addition, the walking distance within a pier is normally not large. Thus if we can assign transfer flights to the same pier, it will facilitate the transfer of passengers.

4.5.2 The Model

Our multi-terminal model can be applied to a multi-pier configuration airport as long as we change the concept of terminal into pier. Instead of the exact walking distance, we consider here the assignment to reduce the "inconvenience" for the transfer passengers. Such inconvenience is measured by the cross-pier transfer walking distance. By doing so, the structure of the model will not be changed except for the definitions in the model. The corresponding definitions referred in the Multi-terminal AGAP Model are changed as follows:

e : pier;

E: the number of piers;

$y_{ii'}^{e}$: equals to 1 or -1 if one of the flights i and i' is assigned to terminal pier e and another is assigned to a different terminal pier; 0 otherwise;

$y_{ii'}$: equal to the cross-pier transfer walking distance between flights i and i' ;

T_e : the set of gates at pier *e*;

ε_e : the distance from pier 1 to pier *e* (*e*=2,…*E*)

Chapter 5 Real-time Gate Recovery Policy for AGAP Problem

Topics in this chapter:

Background

Problem Statement

The Real-time Recovery Policy

Experiment Results

5.1 Background

Due to the increasing deregulation and expansion of airlines, the number of aircrafts grows rapidly in the recent years. Many new flights and flight routes have been added. However, the airport facilities, especially the gates, were not originally designed to handle the increasing traffic volume. As a result, airports face greater challenge in the aircraft-to-gate assignment. One of the great challenges to airports caused by the increasing number of aircrafts and deregulation of airlines is to deal with the flight schedule disruption.

Also, with the increasing number of flights at the airport, one disruption of the flight schedule may affect many other flights. Airports must find an optimal way to minimize the impact of such disruptions. If a disruption happens in the near future, an airport must be able to deal with it in a fast pace so as not to affect other flights' arrival and departure to the gates, while also not to affect the work of the airport service providers. As expected, the demand will further increase in the following years. Though it is possible to ease the problem by building more terminals or expanding the current terminal piers, the short-term solution to solve the airport gate reassignment problem the airport currently faces is still to find a good real-time recovery methodology.

To the best of our knowledge, all the previous works in literature are to deal with the daily planning stage of the aircraft-to-gate assignment, and no systematic analysis has been done in the recovery of the gate assignment in real-time for the AGAP problem. According to our investigation in a hub international airport, the flight schedule disruptions at that airport are frequent. There could be many schedule disruptions daily, though most of the disruptions are slight delays. As a result, the original assignments at the planning stage are frequently violated. Thus, in our work, we propose a Real-time Recovery Policy to deal with the flight schedule disruption problem at the airports.

5.2 Problem Statement

Real-time Gate Recovery is a complicated dynamic process. It must take into account the following factors:

1. Original flight-to-gate assignment;
2. Ground service providers' preparation at the gate;
3. Time tables of the original flight schedule and disrupted flight schedule;
4. Aircraft-gate compatibility;
5. Airline critical transfer flights;
6. Current time point;

Different from the AGAP problem for the planning stage, Real-time Gate Recovery is not to minimize the walking distance for passengers. The most important criterion for real-time recovery is to maintain the original aircraft-to-gate assignment, and the service providers' preparation at the gate if the delay happens in the near future.

In practice, the airport authority may not need to take an action to solve the delay problem if the delay for the passengers is within the "delay tolerance level". For example, for the international hub airport that we observed, the airport authority sets this tolerance level as 20mins since passengers usually do not mind waiting for less than 20mins till the availability of the gate. However, if the waiting time is more than 20mins, the airport authority will have to assign this flight to another gate, or if there is no gate available at that time, the airport authority will have to assign it to a remote stand. In the latter case, passengers will have to take a shuttle bus to get to the terminal building of the airport, which is not preferred by both passengers and the airport authority. Thus, when we solve the real-time gate recovery problem we will allow the waiting time to reach a maximum tolerance, which will be defined by the airport authority according to its experience and practice.

Also, in practice, the airport authority will announce its confirmed gate assignment several hours ahead of the current time and the service provider would pick up the latest information some time in advance so that there will be enough time for them to prepare their ground service facilities for the aircraft at the designated gate. In the practice of the international airport that we observed, such “service turnover time” is one hour ahead of the arrival time of the flight. When the arrival time of the flight is just one hour ahead, the contracted service provider of the aircraft will start to prepare its ground service facilities at the designated gate. This time is the minimum preparation time for the service provider to service the arrival of the aircraft. In practice, any gate reassignment of the flight before the ground service provider starts the preparation does not affect the ground operation of the airport. In addition, as there may be many flight schedule changes in a day, there is not much need for airport to take action every time they are notified unless this change is going to affect or is affecting the current aircraft-to-gate assignment. Thus we propose the Gate Recovery Policy to be divided into two stages: the recovery within the service turnover time ahead of the current time and the recovery after the service turnover time ahead of the current time.

We define the service turnover time as γ hour(s). For those delays that happen within γ hour(s) ahead of the current time, we need to solve the problem immediately as these delays will affect the preparation of the ground service providers in the near future. But for those delays happening after γ hour(s) ahead of the current time, instead of solving the delays each time after being informed by airlines, we will solve the delays as a “batch” at a “trigger point”. Thus there may be many flight schedule disruptions happening after the γ hour(s) time window, but we do not need to solve the problem even though there may be some violation of the assignment constraints because further information is yet to come and we can solve them together. However, this being a dynamic process, the current time is moving forward. When one of the delayed flights that we did not solve when informed by the airlines comes within the service turnover time window of the current time, we will have to take action immediately to solve the problem so that the ground service provider will have enough time for the corresponding preparation at the gate. This time will be the “trigger point” for us to solve the problem of all the delays that may happen after the γ hour(s) time window of the current time as a “batch”. To make the real-time recovery efficient, we propose a recovery policy to solve the delays that happen within γ hour(s) window from the current time immediately using a greedy search, while we solve the delays after the γ hour(s) time window of the current time in batch using our proposed IP Gate Recovery Model.

In daily operations, when a flight is delayed, the airport may receive the request from an airline to assign its "critical transfer flight" to a nearby gate of its designated transfer flight. A critical transfer flight is one in which the passengers need to transfer to another flight in a very short period of time. To assign such flights to nearby gates is very important because passengers may not have enough time for the transfer if the destination gate is too far away. In practice, if such a request is notified more than γ hour(s) in advance, there will not be much problem because we can change our original assignment without affecting the ground service providers' operation. However, if the notification comes in within the γ hour(s) time window of the current time, we cannot change the gate of the critical transfer-out flight within γ hour(s) as the ground service preparation of the arrival of the flight has already started. Instead, we may change the gate of its connecting flight. As the ground occupancy time for a flight includes the alighting service to the arrival passengers, cleaning of the aircraft, boarding preparation and boarding service to departure the passengers etc., the ground occupancy time for a flight is always geater than the service preparation time γ hour(s) in practice. Based on this fact, the recovery of the connecting flight is always in the stage of after the service turnover time of the current time. Thus we propose a Critical Transfer Recovery Procedure for the reassignment of the connecting flight, which is covered in a later section.

5.3 The Real-time Gate Recovery Policy

5.3.1 The Recovery Policy

From a practical point of view, an efficient and effective way to solve the problem of disruption of the original flight-gate assignment by uncertain events is much needed by airports. However, we should not optimize the recovery solely by using the Recovery Model because a greedy search to solve the disruption that happens in the near future, say within the service turnover time γ hour(s), will be more practical and efficient than solving it through an IP model. Here we propose an Airport Real-time Gate Recovery Policy. It is a 2-stage model-combined dynamic optimization process. The first stage would be the Real-time Recovery Policy within the current service turnover time window and the other stage would be the recovery policy optimizing the reassignment after the current service turnover time window.

Our objective, different from the one in previous research works which focus on minimizing passenger walking distance, is to minimize the changes of the original assignment. In addition, as we allow a "delay tolerance" to the flights, we set our objective as minimizing such delays. However, because of the chain effect of flights, delaying one aircraft may also cause subsequent flights to be delayed as well. Thus we are to find an optimal way to minimize the "accumulated delay" both within the current service turnover time window and after the current service turnover time window.

In our solution of the fight schedule disruption, we propose different solving procedure for different types of disruptions. The most frequent event is the early arrival or delayed arrival of the flight. For the early arrival event, the operator can cope with it easily, by letting it wait for an available gate. This is because the passengers expected arrival time is later and thus in such a case, the waiting for an available gate does not create much dissatisfaction for both passengers and airlines.

On the other hand, a flight delay always causes a lot of problems to the original flight-to-gate assignment schedule. There are two kinds of delay: arrival delay and departure delay. Arrival delay and departure delay of a flight may affect the next flight's arrival to the gate. In certain cases when the aircraft occupies a gate too long during peak hours, the number of gates may not be enough. Such delays may cause some of the aircrafts being unable to find an available gate.

Based on the practice of airports, our Real-time Gate Recovery Policy monitors each time point for any changes of flight schedule. According to the time that the disruption is to happen, the recovery policy will use different solving procedures: 1) the Real-time Recovery Policy within the current service turnover time window and 2) the Real-time Recovery Policy after the current service turnover time window.

The steps of the Real-time Gate Recovery Policy are as follows:

Step 1. Get the current time t as the checking time point;

Step 2. Check whether there is any flight schedule disruption information that comes in from the last checking time point to the current time point *t*; if yes, go to Step 3; if no, go to Step 6;

Step3. Check the arrival time of the schedule-disrupted flight t_a. If $t_a < t + \gamma$, where t is the current time, go to Step 4; Otherwise go to Step 5;

Step 4. Calling Real-time Recovery Policy for the 1st planning stage (within the γ hour(s) time window) to solve the disruption, go to Step 6;

Step 5. Calling the Real-time Recovery Policy for the 2nd planning stage (after the γ hour(s) time window) to solve the disruption;

Step 6. Advance the current clock to $t + \Delta t$ and go to Step 1, where Δt is the computational time used for the recovery process;

We will then discuss the details of the corresponding Real-time Recovery Policy for the 1st planning stage (within the γ hour(s) time window) and the 2nd planning stage (after the γ hour(s) time window) in the next two subsections respectively.

5.3.2 The IP Gate Recovery Model

1) Formulation

To deal with the disruptions in far future after the γ hour(s) ahead of the current time as discussed above, the airport authority does not need to take an immediate action right after the disruption information comes because for a busy airport it is frequent that further schedule changes may come in the future. Thus, instead of solving the flight schedule disruption one at a time, the airport can handle these schedule disruptions together as a "batch" using our proposed IP Gate Recovery Model, as long as the flights' corresponding ground service providers' works at the gates have not started.

Different from previous AGAP works which focus mainly on the minimization of the passenger walking distance in the planning stage of the AGAP Problem, the proposed IP

Gate Recovery Model is to give an optimal reassignment with minimum changes to the original gate planning and minimum flights delay as well.

The Airport Gate Assignment IP Gate Recovery Model we propose is as follows:

$$\text{Min } Z = \theta \sum_{i} \sum_{j} \sum_{t} G_{ij} X_{ijt} + \sum_{i} \sum_{j} \sum_{t} t X_{ijt} + M \sum_{i} \sum_{j=n+1}^{n+K} \sum_{t} X_{ijt}$$

S.t.: $\sum_{j=1}^{n+k} \sum_{t} X_{ijt} = 1;\ \forall\, i;$ (5.1)

$\sum_{(i,t)} \sum_{\in I_s} X_{ijt} \le 1;\ \forall\, j, s;$ (5.2)

$X_{ijt} = 1;\ \forall\, i \in \{R\}, j, t;$ (5.3)

X_{ijt} = 0 or 1; for all the i, j, t;

2) Illustration of the Recovery Model

The first part of the objective function $\sum_{i} \sum_{j} \sum_{t} G_{ij} X_{ijt}$ is to measure the changes of the original assignment. G_{ij} equals to 1 if here *j* is not the original gate assigned to flight *i*. As the function $\sum_{i} \sum_{j} \sum_{t} G_{ij} X_{ijt}$ is weighted by θ, a sufficiently large number, changes of the original gate assignment will have a higher cost.

The second part of the objective function $\sum_{i} \sum_{j} \sum_{t} t X_{ijt}$ is to evaluate the delay of the flights. In our model, X_{ijt} is the decision variable. It equals to 1 if flight *i* is assigned to gate *j* with a delay time *t*. As mentioned before, if we use 20mins as the 'maximum delay tolerance' of the airport, t could take the value 1, 2, 3, 4, where each unit stands for 5mins of delay, i.e., if t takes the value of 0, then there is no delay for the flight, and if t takes 1, 2, 3, 4, then the delay would be 5mins, 10mins, 15mins and 20mins respectively. Thus $\sum_j \sum_t tX_{ijt}$ is the delay for flight i and $\sum_i \sum_j \sum_t tX_{ijt}$ is the total delay for all the flights. The big M in the third part of the objective $M\sum_i \sum_{j=n+1}^{n+K} \sum_t X_{ijt}$ is to give the remote stands a penalty cost, which is a sufficiently large number. However, when there is no feasible solution for the fixed gates in the airport even when flights are delayed or changed, some flights will have to be assigned to the remote stand. Thus the assignment to the remote stand has a higher cost in the objective function.

Constraint (5.1) is to make sure that each flight is assigned to a fixed gate or remote stand. Constraint (5.2) is to make sure that at each checking time point, there will be no more than one flight assigned to a gate. Different from the decision variables in the previous AGAP IP models, in the IP Gate Recovery Model each decision variable stands for not only a flight's gate assignment but also the flight's delay choice. Thus to make sure that at any time there will not be more than one aircraft assigned to a gate, we need to consider the possible delay choice of each flight. To effectively formulate our Ground Time Conflict Constraints, we do not formulate the constraint one flight by one flight, but according to each checking time point s. For each checking time point, we find out all the flights with delay choices that have ground time overlap this checking time point and put the corresponding subset (i,t) in the set I_s. For example, if flight *3* with delay choice *2* and flight *5* with delay choice *1* both have ground times overlap at the 4th checking point then (*3*, *2*) and (*5*,*1*) will be put into the set I_4 as subsets. Constraint $X_{3j2} + X_{5j1} \le 1, \forall j$ is formulated according to the I_4 then. In comparison with formulating the Ground Time Conflict Constraints according to each flight with each delay choice, this formulation is much more effective and efficient. Further improvement can be made through using a preprocessing to reduce the redundant constraints. The time checking time interval can be set by the airport authority, when the arrival and departure time of the flights are rounded to the nearest 5mins, the checking time interval can be set as 5mins, i.e., for each 5mins from the starting time of the planning horizon, we will check the ground time overlapping of the flights with delay choices.

Constraint (5.3) is to prevent reassignment of those aircrafts that are currently getting ground service or have been prepared for service, as well as those important flights such as VIP flights and Critical Transfer Flights. We need constraint (5.3) to capture the non-reassign flights because a key point for IP Gate Recovery Model is that it should respect the assignment history. Some gates may be occupied beyond the starting time of the planning of the Recovery Model. Flights in such gates should not be reassigned. Also, for some gates where the ground service providers have already started the preparation of the arrival of the flights or if the arrival is within the service turnover time, we should not reassign such flights so as to give enough time to service providers for the preparation work. Thus when we call the IP Gate Recovery Model to optimize the reassignment of all the flights after the service turnover time window we will not change the assignment of those flights within the service turnover time window.

In order not to disrupt some of the important flights in the original gate assignment schedule, we put the following flights into our Non-reassign Flight Set $\{R\}$ so as not to reassign them by the Recovery Model:

1) Critical transfer flights;

2) VIP flights;

VIP flights are those flights with important passengers. Such flights will be designated to certain gates with VIP service. To avoid reassignment, the values of the corresponding decision variables of the flights in the Non-reassign Flight Set will be set to 1.

5.3.3 Real-time Recovery Policy for the 1st planning stage

The Real-time Recovery Policy for the 1st Planning Stage is to solve the disruption that happens within the γ hour(s) time window of the current time. There are many possibilities in the type of delays. For arrival delay, we will check whether it affects the next flight at the gate. For example, in the practice of one of the international hub airports, the tolerance level is 20mins. To generalize the discussion, we define the tolerance level as δ mins. If the influence is less than δ mins, it is acceptable. However, if the next flight is affected by more than δ mins, we will have to reassign the next flight. Here, we do not reassign the flight that is delayed but only to reassign its next flight. This is because the arrival delay will be within the current service turnover time window and any change of gate of the delayed flight will affect the ground service providers' preparation work at the gate. As we assume according to the airport practice that a flight always occupies a gate for more than γ hour(s) to load and unload passengers, the next flight for the gate is to arrive after the γ hour(s) time window of the current time. We can call our IP Gate

Recovery Model to reassign the next flight. Similarly, for the departure delay, we also need to reassign the next flight by calling the IP Gate Recovery Model if the next flight at the gate is after the γ hour(s) time window. However, for departure delays, it is possible that the affected next flight is within γ hour(s). In such a case, when the next flight is affected by more than δ mins, we will solve the problem using a Greedy Search Algorithm, which is to solve the reassignment problem in the near future within the γ hour(s) time window of the current time. The Greedy Search Algorithm does not change any flight-to-gate assignment within γ hour(s) so as not to influence the ground service providers' preparation at the gate.

Our proposed steps of the **Real-time Recovery Policy for the 1st Planning Stage** within γ hour(s) time window of the current time are as follows:

Step 1. Check the type of disruption; If it is a critical transfer disruption, call the **Critical Transfer Recovery Procedure** to solve the disruption, go to Step 8; If it is a delay disruption, go to Step 2;

Step 2. Check the type of the delay; If it is an arrival delay, go to Step 3; If it is a departure delay, go to Step 5;

Step 3. Check whether the next flight at the gate is affected by more than δ mins; If yes, go to Step 4; If no, do not change the assignment, go to Step 8;

Step 4. Call the **IP Gate Recovery Model** to reassign the next flight; go to Step 8;

Step 5. Check whether the next flight at the gate of the delayed flight is within the γ hour(s) time window of the current time; If yes, go to Step 6; If no, go to Step 4;

Step 6. Check whether the next flight at the gate is affected by more than δ mins; If yes, go to Step 7; If no, do not change the assignment, go to Step 8;

Step 7. Use the **Greedy Search Algorithm** to optimize the reassignment of the next flight;

Step 8. Stop;

The **Greedy Search Algorithm** is as follows:

Step 0. *Initialization.* Put all the gates except the original gate of the flight in Gate Set {G};

Step 1. Select the first gate in Gate Set {G};

Step 2. Check whether the flight is compatible with the gate. If yes, go to Step 3; If no, go to Step 5;

Step 3. Check whether the reassignment of the flight to the gate will affect the flight or the subsequent flight at the gate by more than δ mins. If yes, go to Step 5; If no, go to Step 4;

Step 4. Calculate the "Accumulated Delay" of the reassignment of the flight to the gate.

The Accumulated Delay of gate = the delay of the flight reassigned to the gate + the delay of subsequent flights caused by the reassignment

Step 5. Check whether this gate is the last gate in Gate Set {G}; If yes, go to Step 6; If no, select the next gate in Gate Set {G} and go to Step 2;

Step 6. Check whether any of the gates in Gate Set {G} has been calculated with the "Accumulated Delay"; If yes, go to Step 7; If no, go to Step 8;

Step 7. Assign the flight to the gate with the minimum "Accumulated Delay"

Step 8. Assign the flight to the remote stand;

The Greedy Search Algorithm is used to find the optimal reassignment of a flight within the γ hour(s) time window. As we can see that any delay within the γ hour(s) time window must be solved immediately, we actually deal with the flight reassignment one by one. However, the reassignment must satisfy certain constraints such as the compatibility of the gate and the maximum delay tolerance. In addition, we should also find a solution that leads to a minimum total delay to flights. In our searching algorithm, Step 2 is to check the compatibility of the gate. Step 3 is to check whether the reassignment is feasible so that there is not any flight affected by more than δ mins. Step 4 is to calculate the delay of the affected flights. As we can see, it is not only that the reassigned flight is delayed, but the subsequent flights may also be affected. Thus instead of only calculating the delay of the reassigned flight we should add up all the affected delays. The gate with minimum accumulated delay is our preferred gate to reassign the flight to. However, it is also possible that there is no feasible gate for reassignment. In such a case, no “Accumulated Delay” will be calculated for any gate. Thus the function of Step 6 is to check whether there is any feasible gate for reassignment. Through these steps, the Greedy Search Algorithm can find the feasible recovery solution with minimum accumulated delay.

In the practice of airports, there is another important criterion in the assignment of flights to gates, i.e., the critical transfer. However, this critical transfer assignment is according to the airline’s request. When the airport is notified by the airlines, critical flights will have to be assigned to nearby gates so that passengers on the flight could transfer to another flight as soon as possible. When the request is received, the airport first needs to check whether the flight has been originally defined as a critical transfer flight. If so, the airport authority should have already assigned the critical transfer flights to nearby gates in the daily planning stage and the airport does not need to reassign the flight in such a case. Otherwise, the airport should use the Critical Transfer Recovery Procedure to assign the critical transfer flight to a nearby gate.

The **Critical Transfer Recovery Procedure** is as follows:

Step 0. *Initialization*. Get the Nearby Gate Set {*N*} of the gate that is assigned to the Critical Transfer-out Flight;

Step 1. Select the first gate in the Nearby Gate Set {*N*}; Select the Critical Connecting Flight of the Critical Transfer-out flight;

Step 2. Check whether the Critical Connecting Flight is compatible with the gate. If yes, go to Step 3; If no, go to Step 5;

Step 3. Check whether the reassignment of the flight to the gate will affect the flight or the subsequent flight at the gate by more than δ mins. If yes, go to Step 5; If no, go to Step 4;

Step 4. Calculate the "Accumulated Delay" of the reassignment of the flight to the gate.

The Accumulated Delay of gate = the delay of the flight reassigned to the gate + the delay of its subsequent flights caused by the reassignment

Step 5. Check whether this gate is the last gate in the Nearby Gate Set {G}; If yes, go to Step 6; If no, select the next gate in the Nearby Gate Set {G} and go to Step 2;

Step 6. Check whether any of the gates in the Nearby Gate Set {G} has been calculated with the "Accumulated Delay"; If yes, go to Step 7; If no, go to Step 8;

Step 7. Assign the flight to the gate with the minimum "Accumulated Delay", go to Step 10 ;

Step 8. Call the IP Gate Recovery Model to optimize the reassignment together with all the delays after the γ hour(s) time windows in the Schedule Disrupted Flight Set {S} while setting all the decision variables of the critical flights to be zero if the corresponding gate is not in the Nearby Gate Set {N};

Step 9. Set the Delayed Flight Set {D} to be Ø;

Step 10. Stop;

Critical flights assignment is an important issue for airports. During daily planning, the airport should have assigned those flights to nearby gates according to the airline's information so as to minimize the transferring time for passengers. However, in practice, an emergency request of an airline, which is not in daily planning may come in within the γ hour(s) time window. In such a case, the ground preparation should have been ready for the transfer-out flight at the originally assigned gate. The ground service providers would not be able to have enough time to change the preparation of the arrival of the flight to another gate. Thus, instead of reassigning the transfer-out flight, we will reassign its connecting flight. As we have mentioned, during the daily planning stage, the airport authority should have already assigned the critical flights to nearby gates. Thus when the airport receives the airline request, the airport may check whether the delayed flight is originally a critical flight. If so, the airport does not need to take any action because the critical flights should have been assigned at nearby gates. We will only consider the reassignment of the critical connecting flight when it is originally not a critical flight.

However, we will not consider the assignment of the Critical Connecting Flight to all the gates but only gates in the Nearby Gate Set of the critical flight. This Nearby Gate Set can be defined by the airport authority according to the physical condition of the airport. Each gate has its own Nearby Gate Set, in which all the gates that are within reasonable distance for passengers to catch an urgent connecting flight should be considered. Also, before we resort to the Recovery Model, we should check the necessity of using the model. Thus we use Step 0 to initialize this gate set. In our Critical Transfer Recovery Procedure, we use Step 6 to check whether there is any gate in the Nearby Gate Set possible for the reassignment of the flight. A flight is only possible for reassignment when it is compatible with some gate and feasible with less than δ mins of delay, which is checked through Steps 2 and 3. If there are gates available for the reassignment, we will choose the assignment of the gate that causes minimum "Accumulated Delay" as in our Steps 4 and 7. If there is no gate available through these Greedy Search Procedures, we will have to resort to the IP Gate Recovery Model to solve it through flight swaps. In addition, the IP model solves altogether the reassignment of the schedule disruptions after the γ hour(s) time window. The disrupted flights are stored in the Schedule Disrupted Flight Set $\{S\}$ each time the airport is notified of a schedule change in advance of more than γ hour(s). After the solving of the recovery problem after the γ hour(s) time window, we will set free the $\{S\}$ through Step 9 in the Critical Transfer Recovery Procedure.

We can see that the Critical Transfer Recovery Procedure is actually a combination of the Greedy Search Algorithm and the IP Gate Recovery Model solution. If it is possible for a feasible solution to be obtained through Greedy Search, we will not resort to the Recovery Model so as to make the procedure more efficient. When there is no solution found through the Greedy Search, we will resort to the IP Gate Recovery Model to take into account of all the flights, including those schedule-disrupted flights for optimal recovery solution for the critical transfer and disruptions together. By doing so, the critical transfer flight may not have to be assigned to a remote stand even when there is no feasible solution found by Greedy Search because the possibility of flight swaps is brought in by the Recovery Model, which considers all the flights in the planning stage after the γ hour(s) time window.

5.3.4 Real-time Recovery Policy for the 2nd planning stage

Above is the discussion of the Real-time Recovery Policy for the 1st Planning Stage within the γ hour(s) time window. For the 2nd Planning Stage, i.e., after the γ hour(s) time window, we will solve the disruptions as a batch instead of one by one. This is because the airline flight disruption information is frequent and repeated. It is even possible that a flight may change the schedule several times before it can be confirmed. Thus we will not solve the disruption as soon as we receive the delay information but to wait till a trigger point. The trigger point is defined as the earliest arrival time of the delayed flight. When the time γ hour(s) after the current time is equal to the trigger time, we will call our model to solve the disruptions after γ hour(s) together so as to minimize the impact to the original assignment. The reason that we set γ hour(s) after the current time is to give the ground service providers enough time for the confirmation of the assignment so as to prepare for the arrival of flights.

Thus the **Real-time Recovery Policy for the 2nd Planning Stage** after the γ hour(s) time window of the current time is as follows:

Step 1. Put the delayed flight into the Schedule-disrupted Flight Set $\{S\}$;

Step 2. Check whether there is any flight in the Schedule-disrupted Flight Set $\{S\}$ with arrival time $t_a \le t + \gamma$, where t is the current time; If yes, go to Step 3; If no, go to Step 4;

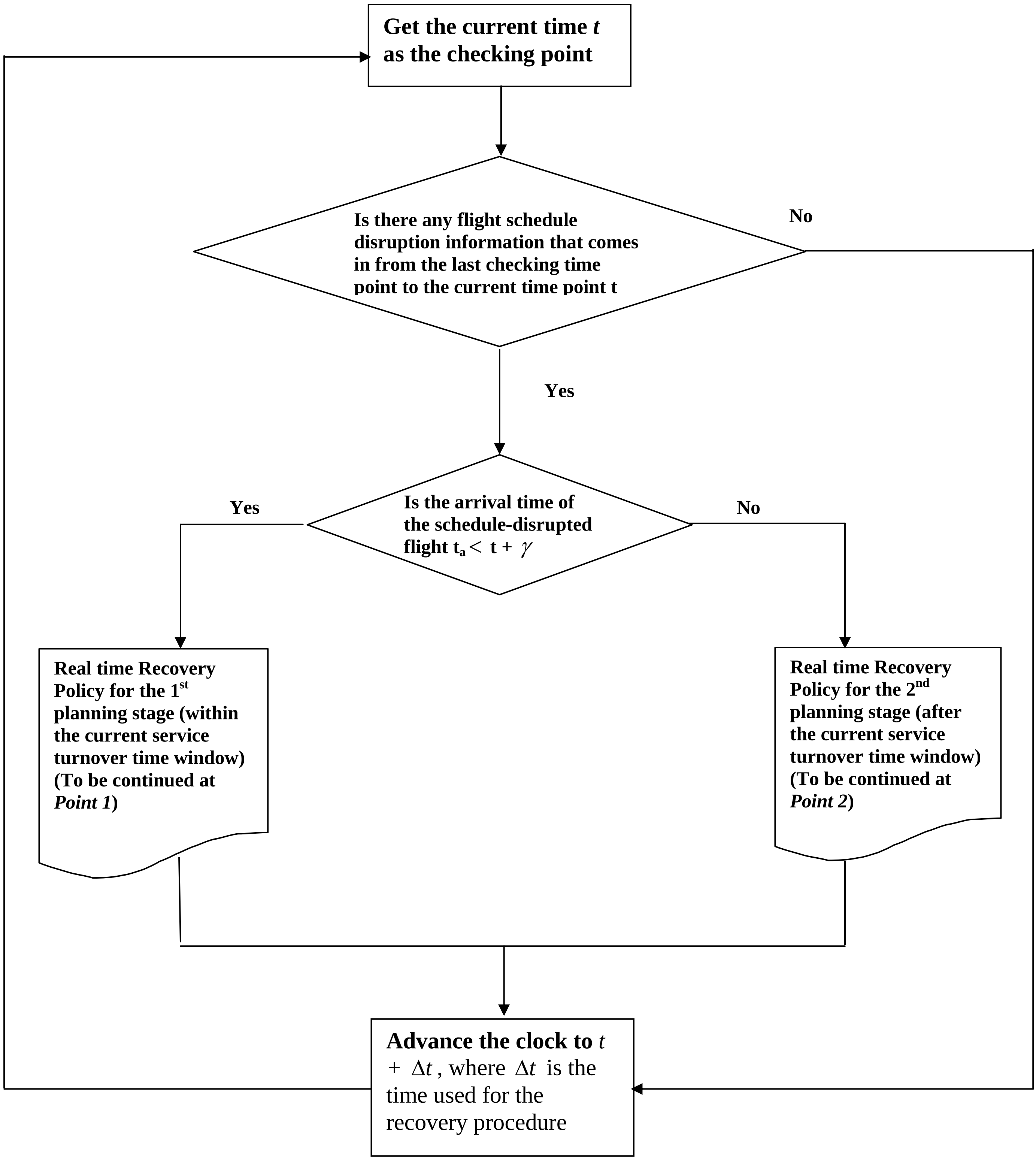
Step 3. Optimize the assignment of all the delayed flights in the Schedule-disrupted Flight Set $\{S\}$ by calling the IP Gate Recovery Model;

Step 4. Set the Schedule-disrupted Flight Set $\{S\} = \varnothing$;

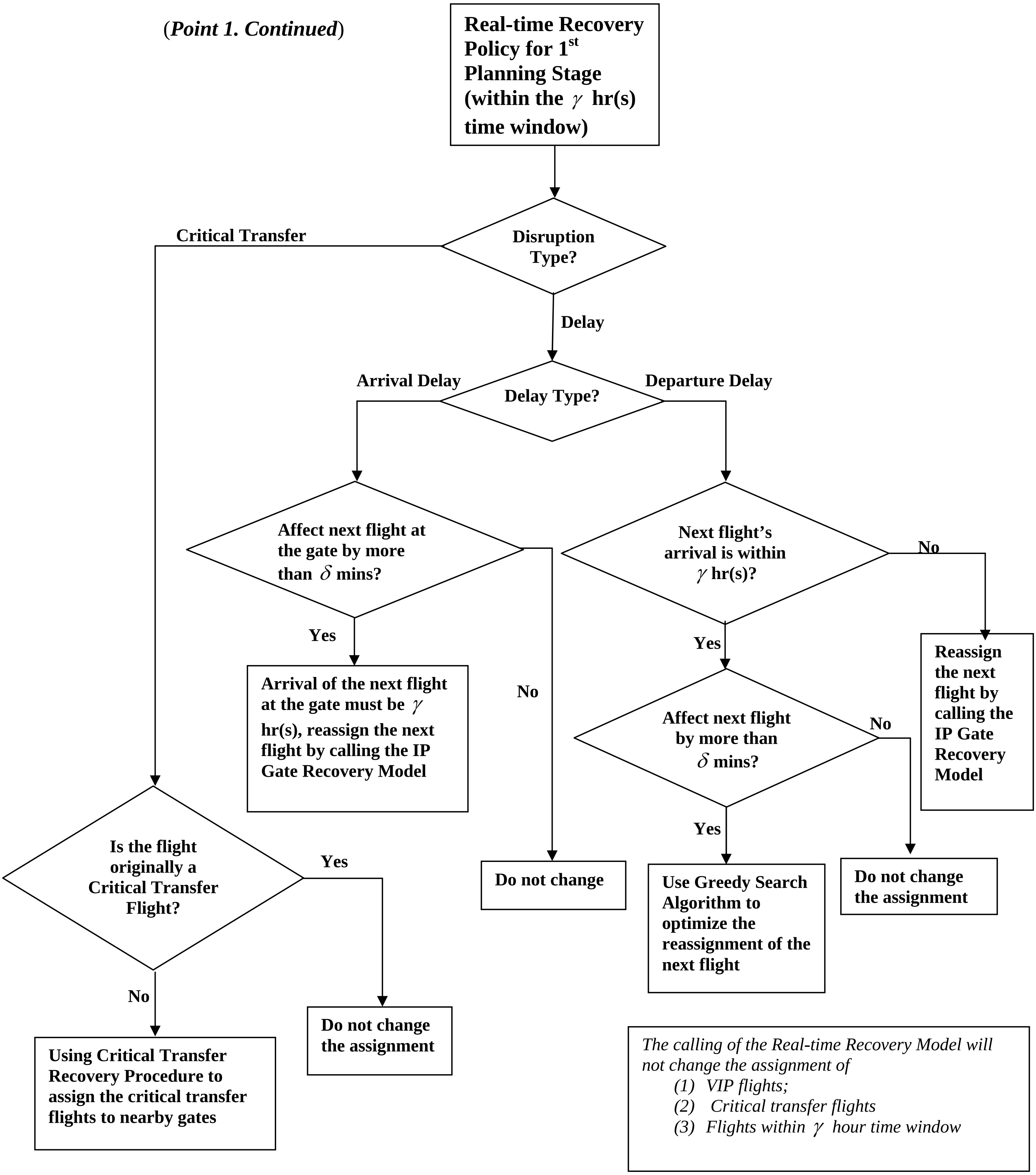
Here Step 2 is used to check the trigger time point while Step 4 is to empty the delayed flight set after optimization as all the delays have been resolved.

In general, the Real time Gate Recovery Policy can be shown by the following flow chart:

Real-time Gate Recovery Policy



(*Point 1. Continued*)



(Point 2. Continued)

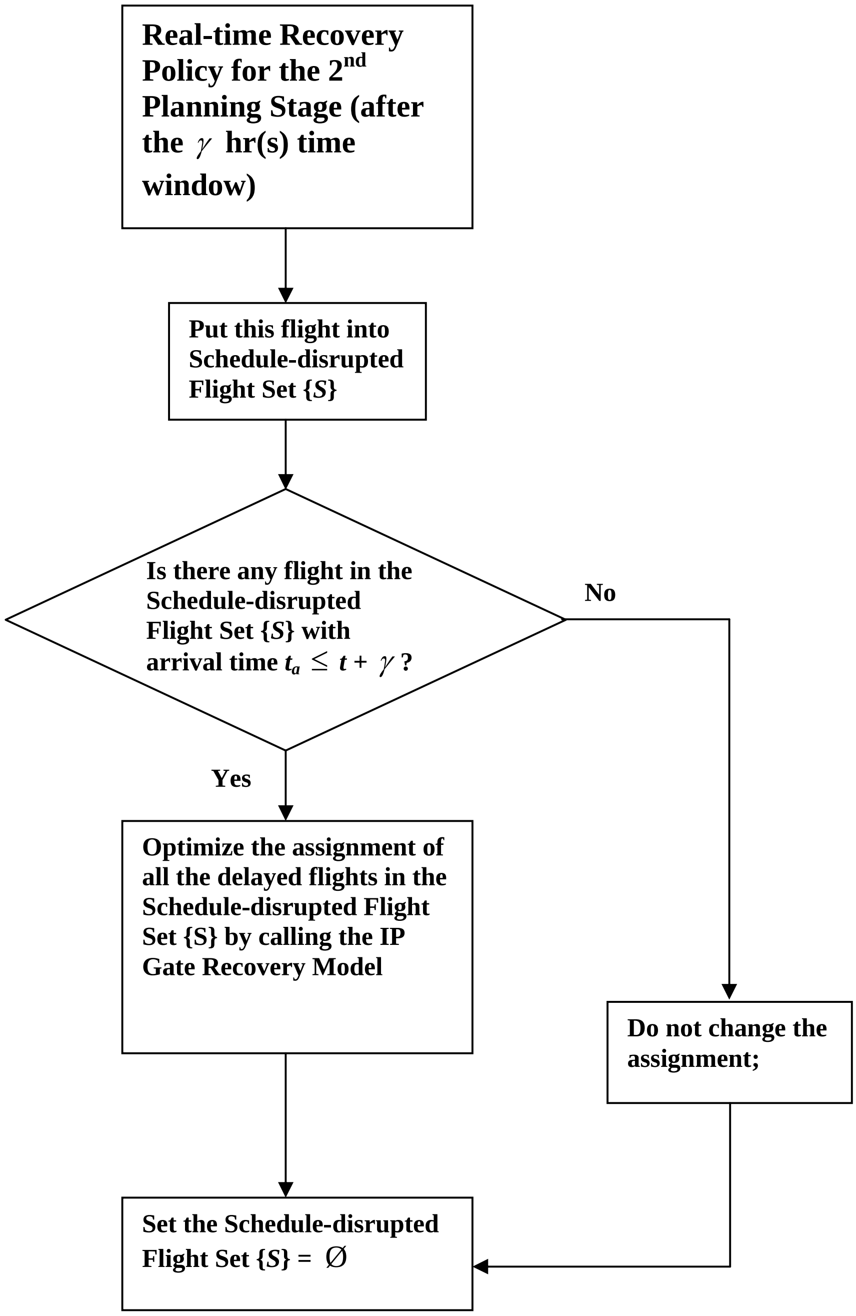


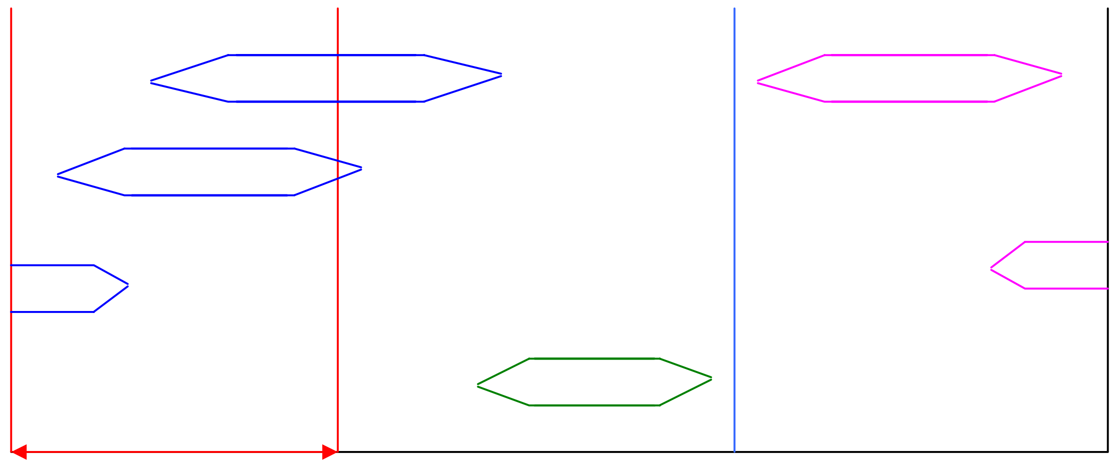
Figure 5.1 Real-time Gate Recovery Policy

5.3.5 Extended Discussion of the Recovery Policy

In order to extend our discussion to the airports with greater gate usage demands or flight schedule disruptions, we propose the procedure of solving the segmented problem rather than the whole problem to make the solution procedure more efficient.

As we can see in our Recovery Policy, we actually divide our recovery into 2 stages: within the γ hour(s) time window and after the γ hour(s) time window, while actually the γ hour(s) time horizon for the planning is defined by the airport authority according to its own practice. When we are using the IP model to optimize the reassignment for the second stage, we actually optimize till the end of the daily planning horizon. However, an optional way for solving the problem more efficiently is to define a "planning level" for the second stage. The planning level can be defined as the number of schedule disrupted flights we are to solve using our IP model. Thus this planning level will decide the size of the problem. The lesser the delayed flights we are to solve, the higher is the solving efficiency. For the rest of the schedule-disrupted flights, we can solve them in our further optimization in the next run. Thus by solving a segmented problem, we can improve the computation efficiency of the IP model to deal with a large-scale problem.

To generalize our solution procedure, we define t_p as the first planning time window for the airport, which actually should be the ground service preparation time γ for the airport. In our previous discussion, t_p is set as one hour(s) according to the practice at the international airport we observed. As t is the current time, which is dynamically moving forward, we define y as the departure time of the N^{th} delayed flight after time $t + t_p$ or the departure time of the last delayed flights if there are less than *N* delayed flights after time $t + t_p$. Here the number *N* is actually our "Planning Level" for the segmented problem, which could be defined by the airport authority according to the efficiency of the solution to their airport. In addition, we define *z* as the end time of our daily planning. Thus we can express our planning time window into 3 stages: from current time *t* to $t + t_p$; from $t + t_p$ to time point y; from *y* to *z*. For delays within the first stage, we will use our Greedy Search for an optimal reassignment. For delays within the second planning stage, we will call our IP Gate Recovery Model to solve the reassignment problem of the *N* delayed flights. For the delays from time point y to *z*, we will postpone the solution till the next trigger point. The planning stages can be shown as follows:



Current time *t* $t + t_p$ *y* *z*

1st Planning Stage: Greedy Search *2nd Planning Stage: Real-time Recovery Model* *3rd Planning Stage: Further Trigger Point*

Figure 5.2 Recovery Planning Stages

Thus we can generalize our solution algorithm as follows:

Step 1. Initialization. Get current time t as the checking time point;

Step 2. Check whether there is any flight schedule disruption information that comes in from the last checking time point to the current time point t; If yes, go to Step 3; If no, go to Step 6;

Step 3. Check the arrival time t_a of the schedule-disrupted flight; If $t_a < t + t_p$; solve the disruption using "Recovery Policy for 1st Planning Stage" and go to Step 6; If not, put this flight into the Schedule-disrupted Flight Set{S},go to Step 4;

Step 4. Check all the arrival times t_a of the flights in the Schedule-disrupted Flight Set {S}; If there is any $t_a \le t + t_p$, call the IP Gate Recovery Model to solve all the flights within the 2nd planning stage from $t + t_p$ to time point y, where y is the departure time of the N^{th} delayed flight after time $t + t_p$ or the departure time of the last delayed flights if there are less than N delayed flights after time $t + t_p$; If there is none, go to Step 6;

Step 5. Set the Schedule-disrupted Flight Set {S} = Ø;

Step 6. Advance the current clock to $t + \Delta t$ and go to Step 1; where Δt is the time used for the recovery process;

As the airport may define their preferred planning time t_p and planning level N according to the efficiency of the solution, this generalized solution algorithm can be customized to airports based on their own practice. In general, the checking frequency for the schedule disruption information can be set as one minute in practice. However, an alternative way is to round the arrival/departure time as well as the delays of flights into a short time interval such as 5 minutes and set the checking frequency as 5 minutes. This brings additional efficiency for the solution procedure. For airports with large demands and many daily schedule disruptions, these procedures make the algorithm suitable for their usage.

5.4 Experiment Results:

5.4.1 The IP Gate Recovery Model

1) Experiment Design

A key issue to cope with flight schedule disruptions at the airport is that the Real-time Recovery must be completed within reasonable time so that the information of the gate reassignment at the airport could be updated in time. Based on the planning flight schedule and the actual flight schedule at the airport, we design our experiment to test the efficiency of the IP Gate Recovery Model. Sensitivity analysis is also done to see the effect of changing the number of delay choices to the gate recovery solution. We also include the analysis of the reassignment pattern to achieve a better understanding of the gate recovery solution.

To see the effect of recovery better, we choose a particular busy day of an international airport to structure our data. There are two sets of input data for our modeling test. The first set of data is the original flight schedule of all the airlines at the airport on the day and the other set of data is the actual flight schedule that includes schedule disruptions. Based on these two sets of data, we can get to know the actual delay to each flight at the airport. The original flight schedule is from the latest schedule brochure announced by the airlines. This is the basis of the gate assignment planning for the airport. For all the gate maintenance on the day, we regard them as special flights, which occupy the gates from the starting time to the ending time of the maintenance to the end time of it. Based on the flight schedule and gate maintenance information, we used our Basic AGAP Model as illustrated previously to achieve the optimal gate assignment solution. The corresponding decision variables of the gate maintenance are set to be 1. The flight schedule disruptions, as well as the gate maintenance, are also incorporated into the IP Gate Recovery Model.

The experiment procedure can be illustrated by the following flow chart:

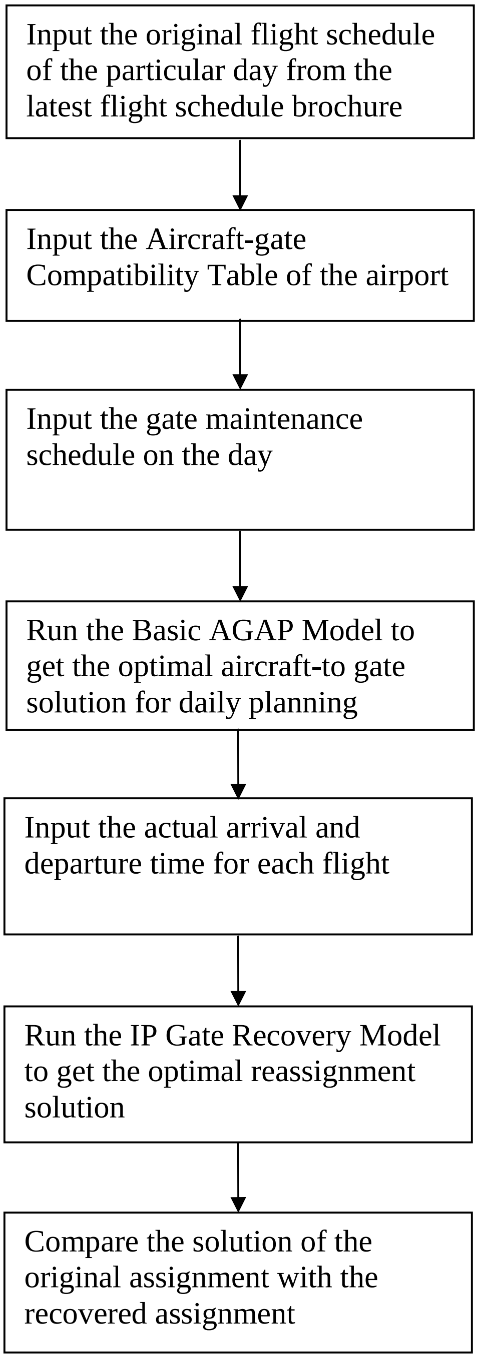


Figure 5.3 Experiment Procedure for the IP Gate Recovery Model

2) Computational Time

To test the efficiency of the IP Gate Recovery Model for the actual recovery problem of the airport, we generate 15 random cases of the disruptions to the original schedule on a particular day. There are 172 flights with 8 gate maintenance tasks on the day to be assigned to 34 gates. Our proposed model can solve each case in less than 40 seconds under CPLEX 7.5 with the same hardware condition as the previous experiments. The average CPU time to solve the models is 36.01 seconds, which indicates the possibility of a practical application of the model to real problems at airport. The results are shown as follows, where the first case is the actual flight schedule disruption problem from airport:

Table 5.1 IP Gate Recovery Model computational time

Model Type	Problem Size*		Case	Computational Time (second)	Average (second)
	No. of Flight	No. of Gate			
IP Gate Recovery Model	172	34	1	39.10	36.01
			2	32.22	
			3	29.88	
			4	38.31	
			5	37.46	
			6	34.45	
			7	36.32	
			8	36.98	
			9	39.62	
			10	37.41	
			11	36.32	
			12	34.56	
			13	36.62	
			14	37.53	
			15	38.21	
			16	31.22	

* Including 8 gate maintenance tasks.

3) Sensitivity Analysis

The sensitivity analysis was done using the actual airport recovery problem as stated above. We changed the tolerance of the maximum delay allowed for the flights to see the effect of such a change to the gate reassignment solution. For the actual gate recovery problem, there were 3 flights reassigned to different gates and 12 of the flights were delayed when we allow 20mins as the maximum delay. When we reduce the time allowed for delay, we found that the number of flights that have to be changed from their original gate assignment increases, which is not preferred by the airport in practice. In the extreme case that no delay is allowed, there will be 13 flights that have to be reassigned to other gates. The results are as follows, while more detailed recovery assignment could be found in Appendix IX:

Table 5.2 IP Gate Recovery Model Sensitivity Analysis

Model Type	Problem Size		4 Delay Choices (Max Delay: 20mins)		3 Delay Choices (Max Delay: 15mins)		2 Delay Choices (Max Delay: 10mins)		1 Delay Choice (Max Delay: 5mins)		No Delay Choice	
	No. of Flights	No. of Gates	Total Number of Gate Change	Total Number of Flight Using Delay Choice	Total Number of Gate Change	Total Number of Flight Using Delay Choice	Total Number of Gate Change	Total Number of Flight Using Delay Choice	Total Number of Gate Change	Total Number of Flight Using Delay Choice	Total Number of Gate Change	Total Number of Flight Using Delay Choice
IP Gate Recovery Model	172	34	3	12	6	9	8	4	11	2	13	0

4) Reassignment Pattern Analysis

To analyze the reassignment pattern of the real-time recovery solutions at different time windows, we ran 20 cases of randomly generated problems. According to the practice of the airport, we divided the planning into three time windows: from 05:00 to 10:00 in the morning, as peak hours; from 10:00 to 19:00, as non-peak hours; and from 19:00 to 23:59, as peak hours. During the time window from 00:00 to 05:00, as there is no flight arrival and departure at the airport, we did not include it in the planning time horizon. The details of the reassignment results could be referred to in Appendices VI, VII and VIII.

Through the analysis of the reassignment pattern, we found that the solution does not guarantee that the reassigned flights are the delayed flights. If some aircraft's arrival is announced to be delayed and will affect the subsequent flight at the gate, it is possible that the subsequent flight is assigned to an empty gate even when it is also possible to reassign the one that is delayed. In practice, we found that the airport authority prefers to reassign the flight that is delayed rather than the subsequent one, which is not due to possible complaint from the non-delayed flight, unless the reassignment of the delayed flight will cause more changes to the original assignments or delays to the other flights. According to the findings on the analysis of the reassignment pattern, one way to solve the problem is to modify the cost coefficient G_{ij} in the IP Gate Recovery Model. The value of G_{ij} can be defined as: equals to 1 if *i* is a delayed flight and *j* is not the original gate for flight *i*; equals to 2 if *i* is not a delayed flight and *j* is not the original gate for flight *i*; equals to 0 if *j* is the original gate for flight *i*. As our model is to minimize the $G_{ij} X_{ij}$, the solution will give the minimum reassignment of the non-delayed flights. This definition of G_{ij} will not change the minimization of the total flight delays because the delay is taken care of in the second part in the model's objective function.

5.4.2 Real-time Recovery Greedy Search Algorithm

To test the efficiency of the real-time recovery heuristic, we programmed the parts of the Greedy Search Algorithm not related with the IP model into C++ computer language. As the heuristic is introduced to solve the real-time recovery problem within the service turnover time, we are to find the solution with minimum accumulated delay for the reassignment satisfying gate compatibility without resorting to the Recovery Model. Different from the recovery for the planning stage, the real-time recovery problem within the service turnover time must be solved in a short period of time as such reassignment is tightly related to the current decision of the airport authority and the ground service providers. In our experiment design, we set the service turnover time as one hour, according to the real practice at the international airport we observed.

To make the experiment practical and instructive to solve the real problem, we used the actual schedule at the airport to test the efficiency of the heuristic. There are 16 randomly generated cases with different delays, each of which is more than 20mins to make sure that the reassignment will be done when solving the problem. Using the Pentium III 866MHz CPU, 256M RAM PC and Microsoft C++ 6.0 in Windows XP, the heuristic solved the problem in less than one second for each case, not including the time for file reading and output, and can be seen from the following table:

Table 5.3 Real-time Gate Recovery Heuristic computational time

Experiment	Problem Size		Case	Computational Time (second)	Average (second)
	No. of Flight	No. of Gate			
Real-time Gate Recovery Heuristic	172	34	1	0.65	0.66
			2	0.78	
			3	0.54	
			4	0.81	
			5	0.67	
			6	0.56	
			7	0.70	
			8	0.91	
			9	0.89	
			10	0.44	
			11	0.53	
			12	0.82	
			13	0.51	
			14	0.73	
			15	0.49	
			16	0.56	

Chapter 6 Conclusions

Conclusions

This thesis focuses on the AGAP Problem both on the daily planning stage and the real-time recovery for flight schedule disruptions. We first extended the modeling work in literature to include more practical considerations and criteria in reality. We formulated the airport gate assignment problem into an extended linear integer mathematical programming model. To improve the linearized quadratic IP model for the gate assignment while taking into account the transfer passengers, we proposed a more efficient 3-terminal AGAP Model to minimize the airport cross-terminal transfers for passengers, where the layout of the 3 terminals can be any type. We also extended the 3-terminal AGAP Model into the Multi-terminal AGAP Model for the multi-terminal airport with linearly linked terminals. The Multi-terminal AGAP Model is then extended to a novel Multi-pier AGAP Model which can be applied to airport terminals with the pier-finger layout concept. According to the experiment results, we found that our proposed models can produce good solutions while incorporating the considerations for transfer passengers. For the improved formulation of the linearized quadratic model that we found, it has been verified in our experiment runs to be much more efficient than previous works in literature.

With the understanding of the need of real-time recovery for the AGAP problem in reality, we developed a systematic model-combined two-stage Real-time Recovery Policy to cope with the real-time flight schedule disruptions, which has not been covered in the literature. Experiment results of the IP Gate Recovery Model with the actual data from an international airport show the possibility of applying the model to solve real large-scale schedule disruption problems.

The works in this thesis reveal that with proper modeling techniques and solving methodology, IP modeling can be applied to the real-life large-scale AGAP problem, while satisfying more practical performance criteria that are not included in previous literature.

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Appendix I Experiment Design for the Basic AGAP Model

The experiment runs of the Basic AGAP are based on the actual data on a particular day of an international airport. There are 172 flights to be assigned to 34 gates. In addition, there are 8 scheduled gate maintenances on the day. The maintenance will make some of the gates not available during the maintenance time. As the occupancy of the gate by maintenance is similar with the occupancy of the gate by an aircraft, we create in our model additional decision variables that are not corresponding to the flight-to-gate assignment but to the maintenance. These decision variables are set to be 1 in representation of the gate usage by maintenance. To incorporate the airport information into our model, we have to deal with the following different input data:

1) Flight Schedule;

2) Gate Compatibility Table;

3) Aircraft Identity Table;

4) Aircraft Type;

All the data is the actual structured information from the airport. Firstly, we used the flight schedule and aircraft identity table to identify the flight ground legs. From the aircraft identity table and flight schedule, we know which aircrafts are on the ground and for how long. All such flight information is put into our database in the following form including the aircraft type:

Flight Leg Table

LEG	AcID	AircraftType	ArrivalTime	DepartureTime	ArrivalPaxNo.	DeparturePaxNo.
1	SJK	A6	1450	1700	377	331
2	SJL	A6	2110	2300	357	376
3	SJO	A6	2035	2230	353	367
4	SMA	B1	1705	2035	232	249
5	SMA	B7	1030	1130	335	425
6	SMC	B8	0550	0800	331	416
7	SMC	B1	1215	1330	309	345
8	SMC	B8	2205	2359	314	283
9	SME	A5	1800	1600	238	265
10	SME	B1	2155	2355	167	242
11	SMF	B1	2120	2359	282	210
12	SMG	A5	1445	1700	180	211
13	SMG	B8	2115	2220	223	294
14	SMH	B7	0615	0850	333	297
15	SMH	B7	1440	1640	273	323

The first column is the flight ground leg number and the second column is the aircraft identity. One aircraft may have several ground legs if it operates several flights in a day. The airport matches each aircraft according to its unique identity in the second column. These information is provided by airlines.

The arrival and departure passenger numbers in the last two columns in the database are randomly generated according to the aircraft type and its maximum passenger capacity. Larger aircraft will have a greater possibility to have more passengers.

Also, we need to collect the information of the physical constraints of the airport. They are the layout of the airport and the restrictions on the usage of gates. All these information is installed in a database. It is a static database and does not change daily. An example of this database is shown in the next page. Each of the standard aircraft is listed, as well as all the gates. The corresponding "X" and "Y" denotes whether that type of aircraft can be parked at the gate or not, where "X" means incompatibility.

Gate Compatibility Table

StandardAircraft	GATE 1	GATE 2	GATE 3	GATE 4	GATE 5
B3	X	X	Y	Y	Y
B4	X	X	Y	Y	Y
A5	X	X	Y	Y	Y
A6	X	X	Y	Y	Y
B7	X	X	Y	Y	Y
B8	X	X	X	X	X
I3	X	X	X	X	X
M1	X	X	Y	Y	Y

Another criterion we need to take into account is based on the measurement of the passenger walking distance in the airport. An example of the corresponding database is as follows:

Gate Parameter Table

Gate	ArrivalPassengerParameter	DeparturePassengerParameter
1	220.5	210
2	294	274
3	367.5	249
4	441	430
5	514.5	502

Here the "ArrivalPassengerParameter" column contains the data of the walking distance for arrival passengers at each gate. The "DeparturePassengerParameter" column contains the data of the walking distance for departure passengers at each gate.

The above Gate Compatibility Table and Gate Parameter Table will link with the Flight Leg Table after the towing decision process of the Flight Leg Table. All the aircraft with flight leg more than 5 hours of flight leg will be towed to a remote stand 2 hours after its arrival and will be towed back to some gate 2 hours before its departure, in accordance with the practice of the airport. The flight leg of each aircraft that needs to be towed will be split into two flight legs. Each of them denotes one decision variable. After this towing decision process, we will calculate the walking distance variable and the compatibility for each decision variable based on all the information on the above tables. We wrote a C++ program to model the objective function and constraints automatically.

After these steps we solved the model using CPLEX 7.5. There are several important outputs. One of them is the gate assignment solution. This tells us which aircraft is assigned to which gate. Another output is to list all the flight legs that have been split for towing. The final output is the list of flights with departure time on the next day. Because we do the gate assignment on a 24-hour basis all the flights on this list are considered next day when we do the gate assignment again.

Appendix II Experiment Design for Model Comparison

In the case study of the comparison of the linearized quadratic models that proposed by Haghani and Chen(1998) and Mangoubi and Mathaisel(1985) with our proposed New Linearized Quadratic Model and the Multi-terminal Model, we ran the experiment in 16 different scenarios. There are 3 sets of parameters to cover the possible combinations of the situations that may affect the solution. They are: I) The percentage of the transfer passengers; II) The transfer pattern; III) The cross-terminal walking distance;

The percentage of the transfer passengers will take the value of A) 5%; B) 15%. As both the arrival flights and departure flights have their respective transfer passengers, in order to avoid repeated calculation, the 'transfer percentage' we adopted here is actually the percentage of transfer-out passengers for arrival flights only. In such sense, one flight may receive transfer-in passengers from several other flights.

The four different transfer patterns are:

1) A flight transfers to all the other flights that are possible for its transfer;

2) A flight transfers to the nearest departure flight that is possible for its transfer;;

3) A flight transfers to the longest departure flight that is possible for its transfer;

4) A flight transfers to the median departure flight that is possible for its transfer;

The cross-terminal walking distance takes the value of A) 100; B) 30;

The total number of cases under these different parameters is 16. We compared the results of the 16 cases in different scenarios as follows:

No.	Cross-Terminal Walking Distance	Percentage of Transfer Passengers	Transfer Pattern
1	100	5%	(1) A flight transfers to all the other flights that are possible for its transfer;
2			(2) A flight transfers to the nearest departure flight that is possible for its transfer;
3			(3) A flight transfers to the longest departure flight that is possible for its transfer;
4			(4) A flight transfers to the median departure flight that is possible for its transfer;
5		15%	(1) A flight transfers to all the other flights that are possible for its transfer;
6			(2) A flight transfers to the nearest departure flight that is possible for its transfer;
7			(3) A flight transfers to the longest departure flight that is possible for its transfer;
8			(4) A flight transfers to the median departure flight that is possible for its transfer;
9	30	5%	(1) A flight transfers to all the other flights that are possible for its transfer;
10			(2) A flight transfers to the nearest departure flight that is possible for its transfer;
11			(3) A flight transfers to the longest departure flight that is possible for its transfer;
12			(4) A flight transfers to the median departure flight that is possible for its transfer;
13		15%	(1) A flight transfers to all the other flights that are possible for its transfer;
14			(2) A flight transfers to the nearest departure flight that is possible for its transfer;
15			(3) A flight transfers to the longest departure flight that is possible for its transfer;
16			(4) A flight transfers to the median departure flight that is possible for its transfer;

The description of the 3 sets of parameters is as follows:

I) Parameter 1: Percentage of Transfer Passengers = A) 5%; B) 15%;

We here set the maximum capacity of the aircraft to be 600 passengers. According to common practice, we assume 85% of the aircraft passenger seat capacity is occupied. The total numbers of arrival, departure and transfer passengers we set is then 510.

In such an assumption, when the number of transfer passengers makes up 5% of each flight, the number of transfer passengers for each flight is as follows:

Transfer Passenger Number = 5% * Passenger Number		
Flight	**Passenger Number**	**Number of Transfer Passengers**
1	510	26
2	510	26
3	510	26
4	510	26
5	510	26
6	510	26
7	510	26
8	510	26

When the number of transfer passengers makes up 15% of each flight, the number of transfer passengers for each flight is as follows:

Transfer Passenger Number = 15% * Passenger Number		
Flight	**Passenger Number**	**Number of Transfer Passengers**
1	510	77
2	510	77
3	510	77
4	510	77
5	510	77
6	510	77
7	510	77
8	510	77

II) Parameter 2: Transfer Patterns

Given a certain flight schedule, the transfer is only possible from the flight with arrival time earlier than the other's departure time. Thus when we defined the number of transfer passengers, we also followed the flight schedule below to check the possibility of the transfer for each flight pair:

Flight	Arrival Time	Departure Time
1	00:00	00:55
2	01:10	01:50
3	00:30	02:55
4	00:40	01:20
5	01:40	02:40
6	00:50	02:30
7	01:00	02:50
8	02:30	03:10

The three types of transfer pattern considered are as follows:

1) A flight transfers to all the other flights that are possible for its transfer;

For the case of 5% transfer passenger proportion, the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	3	3	4	4	4	4	4	26	484
2	0	0	5	0	5	5	5	6	26	484
3	0	4	0	4	4	4	5	5	26	484
4	0	4	4	0	4	4	5	5	26	484
5	0	0	6	0	0	6	7	7	26	484
6	0	6	0	0	6	0	7	7	26	484
7	0	5	5	0	5	5	0	6	26	484
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	22	23	8	28	28	33	40		
Departure Passenger Number	510	488	487	502	482	482	477	470		

In such case, the number of arrival passengers = 510 – the number of transfer-out passengers = 510-510*5%= 484, where 510, being 85% of the aircraft loading capacity, is the actual load of the aircraft. The number of departure passengers will be calculated according to the composition of the transfer passengers. In such a case, the number of departure passengers equals to (510 – the number of transfer-in passengers), as shown in above the table.

Similarly, for the case of 15% of the passengers is transfer passengers, the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	11	11	11	11	11	11	11	77	433
2	0	0	15	0	15	15	16	16	77	433
3	0	12	0	13	13	13	13	13	77	433
4	0	12	13	0	13	13	13	13	77	433
5	0	0	19	0	0	19	19	20	77	433
6	0	19	0	0	19	0	19	20	77	433
7	0	15	15	0	15	16	0	16	77	433
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	69	73	24	86	87	91	109		
Departure Passenger No.	510	441	437	486	424	423	419	401		

2) A flight transfers to the nearest departure flight that is possible for its transfer;

For the case of 5% of the passengers is transfer passengers, the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	26	0	0	0	0	0	0	26	484
2	0	0	26	0	0	0	0	0	26	484
3	0	26	0	0	0	0	0	0	26	484
4	0	26	0	0	0	0	0	0	26	484
5	0	26	0	0	0	0	0	0	26	484
6	0	26	0	0	0	0	0	0	26	484
7	0	26	0	0	0	0	0	0	26	484
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	156	26	0	0	0	0	0		
Departure Passenger No.	510	354	484	510	510	510	510	510		

For the case that of 15% of the passengers are transfer passengers the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	77	0	0	0	0	0	0	77	433
2	0	0	77	0	0	0	0	0	77	433
3	0	77	0	0	0	0	0	0	77	433
4	0	77	0	0	0	0	0	0	77	433
5	0	77	0	0	0	0	0	0	77	433
6	0	77	0	0	0	0	0	0	77	433
7	0	77	0	0	0	0	0	0	77	433
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	462	77	0	0	0	0	0		
Departure Passenger No.	510	48	433	510	510	510	510	510		

3) A flight transfers to the longest departure flight that is possible for its transfer;

For the case of 5% of the passengers is transfer passengers, the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	0	0	0	0	0	0	26	26	484
2	0	0	0	0	0	0	0	26	26	484
3	0	0	0	0	0	0	0	26	26	484
4	0	0	0	0	0	0	0	26	26	484
5	0	0	0	0	0	0	0	26	26	484
6	0	0	0	0	0	0	0	26	26	484
7	0	0	0	0	0	0	0	26	26	484
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	0	0	0	0	0	0	182		
Departure Passenger No.	510	510	510	510	510	510	510	328		

For the case of 15% of the passengers is transfer passengers, the transfer pattern is as follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8*	Transfer-out Passenger No.	Arrival Passenger No.
1	0	0	0	0	0	0	0	77	77	433
2	0	0	0	0	0	0	0	77	77	433
3	0	0	0	0	0	0	0	77	77	433
4	0	0	0	0	0	0	0	77	77	433
5	0	0	0	0	0	0	0	77	77	433
6	0	0	0	0	0	0	0	77	77	433
7	0	0	0	0	0	0	0	77	77	433
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	0	0	0	0	0	0	539*		
Departure Passenger No.	510	510	510	510	510	510	510	0		

For the case of 15% of the passengers are transfer passengers, if more than 6 flights transfer-in to flight 8, the number of transfer-in passengers will exceed 85% of the aircraft capacity as what was defined earlier. The passenger-load rate in such a case is actually 539/600= 90%. However, for simplification, we allow the passenger-load rate to be exceeded in this case. As a result the departure passenger number of flight leg 8 will be zero. The departure of the flight leg 8 will be a pure transfer-in flight.

4) A flight transfers to the median departure flight that is possible for its transfer;

The median departure flight is the flight between the next nearest flight and the farthest flight. For the case of 5% percentage of the passengers are transfer passengers, the transfer pattern is as the following:

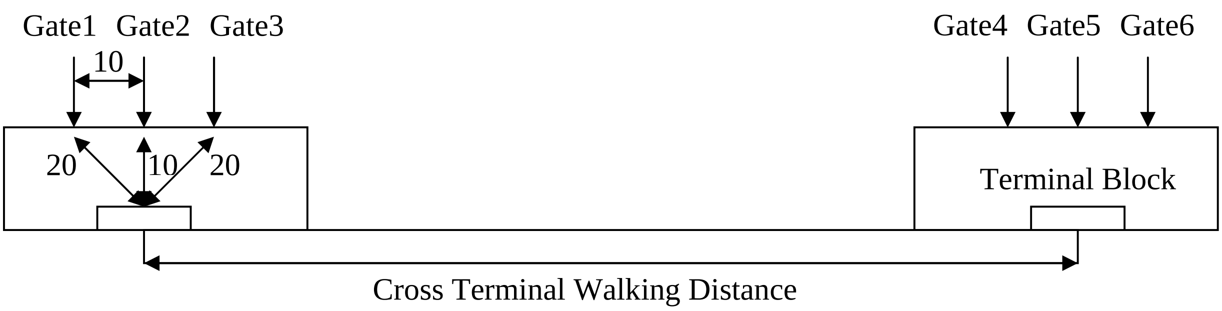
TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	0	0	0	26	0	0	0	26	484
2	0	0	0	0	0	26	0	0	26	484
3	0	0	0	0	26	0	0	0	26	484
4	0	0	0	0	26	0	0	0	26	484
5	0	0	0	0	0	26	0	0	26	484
6	0	0	0	0	26	0	0	0	26	484
7	0	0	0	0	26	0	0	0	26	484
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	0	0	0	130	52	0	0		
Departure Passenger No.	510	510	510	510	380	458	510	510		

For the case of 15% percentage of the passengers are transfer passengers, the transfer pattern is as the follows:

TransferPaxNO.ii'	1	2	3	4	5	6	7	8	Transfer-out Passenger No.	Arrival Passenger No.
1	0	0	0	0	77	0	0	0	77	433
2	0	0	0	0	0	77	0	0	77	433
3	0	0	0	0	77	0	0	0	77	433
4	0	0	0	0	77	0	0	0	77	433
5	0	0	0	0	0	77	0	0	77	433
6	0	0	0	0	77	0	0	0	77	433
7	0	0	0	0	77	0	0	0	77	433
8	0	0	0	0	0	0	0	0	0	510
Transfer-in Passenger No.	0	0	0	0	385	154	0	0		
Departure Passenger No.	510	510	510	510	125	356	510	510		

III) Parameter 3: Cross-Terminal Walking Distance = (1) 100; (2) 30

We designed our gate assignment problem as a 2-terminal linear layout airport gate assignment problem. Gate1, Gate2 and Gate3 belong to terminal 1. Gate4, Gate5, Gate6 belong to terminal 2. The walking distance between two nearby gates is 10 meters. The walking distance from each gate to the terminal block is shown in the following chart together with the airport layout scenario, which Under the scenario of the airport layout, we input the cross-terminal walking distance as 100 or 30 meters to compare the assignment results.



Case Study Scenario: Airport Layout

Appendix III Expected Flight Schedule and Optimal Assignment

Flight LEG	Aircraft Type	ArrivalTime	DepartureTime	ArrPaxNo.	DeptPaxNo.	Optimal Gate Assignment Using Basic AGAP Model According to the Expected Flight Schedule
1	A6	0000	0115	226	206	19
2	B7	0225	0855	216	228	5
3	B7	1500	1650	123	188	5
4	B7	1830	2000	111	196	13
5	B7	2100	2300	333	307	27
6	B7	2320	2359	280	177	14
7	B7	0000	0130	183	217	4
8	A2	0145	0550	263	271	19
9	B7	0750	0945	225	186	19
10	B3	1035	1310	261	260	3
11	A6	1455	1845	347	363	33
12	B7	2025	2140	107	115	3
13	B3	2150	2359	266	215	30
14	B7	0000	0110	397	430	30
15	B7	0430	0825	410	429	16
16	A6	1050	1150	396	430	31
17	B8	1245	1340	228	255	31
18	B8	1415	1515	310	303	14
19	B3	1800	2155	338	268	5
20	B3	2140	2325	311	330	13
21	B7	2335	2359	312	394	13
22	B7	0000	0125	389	424	31
23	B3	0545	0815	472	493	31
24	A4	0815	0955	174	179	12
25	A6	0955	1045	353	414	19
26	B3	1155	1330	421	431	19
27	B2	1345	1515	357	312	18
28	A2	1515	1650	248	249	29
29	B7	1705	1930	382	382	26
30	B6	2015	2145	351	361	2
31	B3	2205	2359	382	348	5
32	A3	0000	0905	119	112	9
33	A4	1710	1900	175	173	29
34	A2	1915	2000	239	232	2
35	A2	2225	2359	279	243	12
36	A4	0000	0755	175	168	12
37	A3	0825	1010	124	122	29
38	A2	1830	2105	280	260	23
39	B7	0000	0725	411	400	32
40	B3	0745	0950	459	479	14
41	B3	1625	2050	477	475	15
42	A5	2130	2205	419	348	4
43	B7	2220	2359	392	402	4

44	B8	0000	0130	488	481	14
45	B8	0655	1015	482	483	34
46	B3	1430	1900	417	426	16
47	B7	2025	2145	431	378	30
48	B8	2225	2359	482	451	31
49	B3	0000	0900	479	472	22
50	B7	1545	1825	431	436	13
51	A6	1915	2105	436	360	19
52	B3	2145	2359	495	426	3
53	A2	0000	0130	247	219	1
54	A2	0740	0935	279	231	32
55	A4	0205	0850	176	165	23
56	A4	1520	1630	165	172	20
57	A3	2205	2359	122	110	6
58	B3	0615	0930	454	411	26
59	B7	1105	1305	422	437	14
60	B7	1535	1845	383	385	22
61	B3	1915	2359	324	349	16
62	B7	0010	0115	379	420	5
63	B7	0545	1030	417	382	8
64	B3	1125	1320	238	212	30
65	B3	1540	1705	290	231	19
66	A2	1840	1930	235	256	21
67	B3	2100	2255	441	369	14
68	B7	0000	0835	411	412	27
69	B7	0915	1100	397	389	5
70	B7	1110	1330	429	433	4
71	B3	1405	1720	497	482	4
72	A4	1910	2035	176	167	33
73	B3	2130	2330	353	329	15
74	A4	0550	0900	176	178	21
75	A4	1205	1400	165	168	29
76	A3	1400	1530	116	122	6
77	A3	1705	1855	111	123	1
78	B6	1915	2100	356	344	29
79	A4	2055	2245	173	169	1
80	A4	2245	2359	164	175	29
81	A3	0000	0810	115	118	29
82	A2	1105	1515	218	260	21
83	A3	1800	1920	113	125	6
84	A3	2215	2359	111	121	23
85	B2	0035	0650	426	396	20
86	B2	0745	0850	223	279	3
87	B2	0850	1015	298	276	18
88	B2	1020	1125	306	335	18
89	B2	1215	1320	349	311	18
90	B2	1225	1500	322	368	1
91	B2	1515	1630	221	279	1
92	B2	1810	1920	325	413	12

93	B2	2015	2135	233	192	18
94	B2	2245	2359	120	180	18
95	B3	0020	0155	317	307	3
96	B7	0540	0735	331	310	3
97	B3	0815	1230	250	294	15
98	B3	1355	1600	300	361	3
99	B3	1650	2105	301	321	32
100	B7	2115	2240	279	308	11
101	B2	0000	0820	467	470	2
102	A2	0835	0925	233	266	2
103	A2	1230	1400	245	250	2
104	B2	1430	1555	316	311	2
105	A2	1845	2035	247	262	20
106	A2	2220	2359	222	257	2
107	B2	0000	0845	390	433	18
108	A4	1510	1620	170	165	15
109	B2	1845	1920	259	298	18
110	A2	2000	2105	235	253	12
111	A3	2215	2359	124	118	21
112	B7	0605	0815	227	195	11
113	B7	0840	1020	199	203	13
114	B3	1135	1525	323	331	22
115	B7	1850	2359	224	237	34
116	A4	0240	0845	175	169	6
117	B2	2055	2359	244	208	20
118	A3	0155	0915	114	110	24
119	A2	0705	0930	233	268	20
120	B8	0630	0955	210	153	10
121	B7	1700	1910	233	297	3
122	B7	1925	2150	399	340	31
123	B8	2135	2330	382	411	33
124	B3	0605	0830	403	364	30
125	B7	0850	1030	432	402	30
126	B3	1445	1700	200	158	30
127	B8	1740	2030	308	289	14
128	B7	2120	2359	327	292	10
129	B3	0655	0905	330	357	4
130	B7	0925	1055	397	392	4
131	B7	1805	2000	301	337	30
132	B3	2145	2359	239	254	32
133	A2	0220	0600	230	252	1
134	A2	0615	0910	268	219	1
135	B7	1100	1215	334	334	13
136	A3	1245	1400	119	112	13
137	A2	1415	1530	268	232	19
138	B2	1615	1715	303	236	18
139	B2	1740	1825	243	312	18
140	B2	1900	2015	282	315	1
141	A2	2030	2100	234	255	21

142	B2	2320	2359	382	339	1
143	B3	0045	0240	333	377	13
144	B7	0555	0650	218	300	19
145	B7	0710	0745	211	203	19
146	A5	0920	1030	380	418	3
147	B7	1050	1150	102	127	19
148	B7	1230	1605	200	203	32
149	B7	1720	1850	339	308	19
150	B3	1935	2315	170	189	26
151	B7	0030	0900	390	407	28
152	B7	0915	1230	402	379	16
153	A2	1420	1540	259	237	13
154	B8	1755	1920	499	479	31
155	B7	2125	2215	430	429	19
156	B7	2240	2359	437	379	22
157	A6	0145	0720	417	382	14
158	B7	0825	1010	402	396	31
159	A2	1210	1515	278	275	20
160	B7	1550	1700	419	425	14
161	A2	1750	1910	253	222	2
162	B7	1950	2230	395	420	22
163	B3	0600	0755	425	499	15
164	B3	0700	0830	416	368	13
165	B7	0920	1100	376	388	22
166	B7	1130	1315	394	426	5
167	B3	1435	1715	464	490	31
168	B3	1925	2015	316	341	3
169	B3	2230	2359	269	231	19
170	B8	0655	0945	332	328	33
171	B3	1750	2100	288	344	4
172	B7	2205	2359	332	318	28
173	Gate Maintenance	0000	2359	0	0	17
174	Gate Maintenance	1000	1700	0	0	12
175	Gate Maintenance	1000	1200	0	0	10
176	Gate Maintenance	0200	0400	0	0	11
177	Gate Maintenance	1000	1700	0	0	23
178	Gate Maintenance	1000	1700	0	0	24
179	Gate Maintenance	1130	1700	0	0	26
180	Gate Maintenance	1200	1700	0	0	34

Appendix IV Actual Flight Schedule with Schedule disruption

Flight LEG	Aircraft Type	ArrivalTime	DepartureTime	ArrPaxNo.	DeptPaxNo.
1	A6	0000	0130	226	206
2	B7	0225	0908	216	228
3	B7	1500	1650	123	188
4	B7	1830	2025	111	196
5	B7	2100	2320	333	307
6	B7	2320	2359	280	177
7	B7	0000	0130	183	217
8	A2	0145	0550	263	271
9	B7	0750	0945	225	186
10	B3	1035	1310	261	260
11	A6	1500	1845	347	363
12	B7	2035	2140	107	115
13	B3	2150	2359	266	215
14	B7	0000	0110	397	430
15	B7	0430	0825	410	429
16	A6	1050	1150	396	430
17	B8	1245	1340	228	255
18	B8	1425	1515	310	303
19	B3	1830	2155	338	268
20	B3	2155	2325	311	330
21	B7	2335	2359	312	394
22	B7	0000	0125	389	424
23	B3	0545	0815	472	493
24	A4	0815	0955	174	179
25	A6	0955	1045	353	414
26	B3	1215	1345	421	431
27	B2	1345	1515	357	312
28	A2	1515	1650	248	249
29	B7	1705	1930	382	382
30	B6	2030	2145	351	361
31	B3	2205	2359	382	348
32	A3	0000	0905	119	112
33	A4	1710	1900	175	173
34	A2	1915	2000	239	232
35	A2	2230	2359	279	243
36	A4	0000	0755	175	168
37	A3	0825	1020	124	122
38	A2	1830	2105	280	260
39	B7	0000	0755	411	400
40	B3	0745	1010	459	479
41	B3	1625	2115	477	475
42	A5	2130	2205	419	348
43	B7	2220	2359	392	402
44	B8	0000	0130	488	481
45	B8	0655	1040	482	483

46	B3	1430	1925	417	426
47	B7	2025	2145	431	378
48	B8	2225	2359	482	451
49	B3	0000	0920	479	472
50	B7	1545	1825	431	436
51	A6	1915	2130	436	360
52	B3	2200	2359	495	426
53	A2	0000	0130	247	219
54	A2	0740	0945	279	231
55	A4	0205	0850	176	165
56	A4	1550	1630	165	172
57	A3	2210	2359	122	110
58	B3	0615	1020	454	411
59	B7	1105	1305	422	437
60	B7	1535	1900	383	385
61	B3	1915	2359	324	349
62	B7	0010	0115	379	420
63	B7	0545	1030	417	382
64	B3	1125	1320	238	212
65	B3	1540	1705	290	231
66	A2	1840	1930	235	256
67	B3	2105	2330	441	369
68	B7	0000	0835	411	412
69	B7	0915	1115	397	389
70	B7	1110	1335	429	433
71	B3	1405	1740	497	482
72	A4	1910	2035	176	167
73	B3	2130	2330	353	329
74	A4	0550	0900	176	178
75	A4	1205	1400	165	168
76	A3	1400	1530	116	122
77	A3	1705	1855	111	123
78	B6	1915	2100	356	344
79	A4	2100	2245	173	169
80	A4	2245	2359	164	175
81	A3	0000	0810	115	118
82	A2	1105	1520	218	260
83	A3	1800	2015	113	125
84	A3	2215	2359	111	121
85	B2	0035	0655	426	396
86	B2	0745	0850	223	279
87	B2	0850	1015	298	276
88	B2	1020	1125	306	335
89	B2	1215	1320	349	311
90	B2	1225	1500	322	368
91	B2	1515	1630	221	279
92	B2	1815	1920	325	413
93	B2	2015	2135	233	192
94	B2	2250	2359	120	180

95	B3	0020	0155	317	307
96	B7	0540	0735	331	310
97	B3	0830	1250	250	294
98	B3	1405	1615	300	361
99	B3	1650	2105	301	321
100	B7	2115	2305	279	308
101	B2	0000	0825	467	470
102	A2	0835	0945	233	266
103	A2	1230	1415	245	250
104	B2	1430	1555	316	311
105	A2	1845	2045	247	262
106	A2	2220	2359	222	257
107	B2	0000	0845	390	433
108	A4	1510	1620	170	165
109	B2	1845	1940	259	298
110	A2	2000	2130	235	253
111	A3	2215	2359	124	118
112	B7	0605	0830	227	195
113	B7	0840	1055	199	203
114	B3	1210	1545	323	331
115	B7	1915	2359	224	237
116	A4	0240	0850	175	169
117	B2	2130	2359	244	208
118	A3	0155	0915	114	110
119	A2	0705	0945	233	268
120	B8	0630	1010	210	153
121	B7	1700	1910	233	297
122	B7	1925	2150	399	340
123	B8	2200	2350	382	411
124	B3	0605	0845	403	364
125	B7	0850	1030	432	402
126	B3	1450	1705	200	158
127	B8	1740	2045	308	289
128	B7	2120	2359	327	292
129	B3	0655	0905	330	357
130	B7	0925	1105	397	392
131	B7	1850	2015	301	337
132	B3	2155	2359	239	254
133	A2	0220	0610	230	252
134	A2	0615	0920	268	219
135	B7	1100	1215	334	334
136	A3	1245	1400	119	112
137	A2	1415	1545	268	232
138	B2	1615	1715	303	236
139	B2	1740	1825	243	312
140	B2	1900	2015	282	315
141	A2	2030	2145	234	255
142	B2	2320	2359	382	339
143	B3	0045	0240	333	377

144	B7	0555	0650	218	300
145	B7	0715	0745	211	203
146	A5	0920	1030	380	418
147	B7	1055	1150	102	127
148	B7	1230	1605	200	203
149	B7	1730	1915	339	308
150	B3	1940	2330	170	189
151	B7	0030	0915	390	407
152	B7	0915	1235	402	379
153	A2	1435	1600	259	237
154	B8	1755	1920	499	479
155	B7	2145	2215	430	429
156	B7	2240	2359	437	379
157	A6	0145	0725	417	382
158	B7	0825	1010	402	396
159	A2	1215	1515	278	275
160	B7	1600	1735	419	425
161	A2	1800	1920	253	222
162	B7	2000	2300	395	420
163	B3	0600	0755	425	499
164	B3	0700	0830	416	368
165	B7	0920	1110	376	388
166	B7	1130	1325	394	426
167	B3	1435	1715	464	490
168	B3	1930	2015	316	341
169	B3	2230	2359	269	231
170	B8	0655	1000	332	328
171	B3	1820	2140	288	344
172	B7	2215	2359	332	318
173	Gate Maintenance	0000	2359	0	0
174	Gate Maintenance	1000	1700	0	0
175	Gate Maintenance	1000	1200	0	0
176	Gate Maintenance	0200	0400	0	0
177	Gate Maintenance	1000	1700	0	0
178	Gate Maintenance	1000	1700	0	0
179	Gate Maintenance	1130	1700	0	0
180	Gate Maintenance	1200	1700	0	0

Appendix V Comparison of the Gate Assignment of Original Planning and Recovery with no Delay for Actual Problem

GATE	Original Assignment						Recovered Assignment			Flight-Gate Assignment Recovery Due to Schedule Disruption
	Original Flights Assigned to Gate	Aircraft Type	Expected Arrival Time	Expected Departure Time	Actual Arrival Time	Actual Departure Time	Reassigned Flights to Gate	Actual Arrival Time	Actual Departure Time	
1	53	A2	0000	0130	0000	0130	53	0000	0130	
	133	A2	0220	0600	0220	0610	133	0220	0610	Flight Delayed
	134	A2	0615	0910	0615	0920	134	0615	0920	Flight Delayed
	90	B2	1225	1500	1225	1500	90	1225	1500	
	91	B2	1515	1630	1515	1630	91	1515	1630	
	77	A3	1705	1855	1705	1855	77	1705	1855	
	140	B2	1900	2015	1900	2015	140	1900	2015	
	79	A4	2055	2245	2100	2245	79	2100	2245	Flight Delayed
	142	B2	2320	2359	2320	2359	142	2320	2359	
2	101	B2	0000	0820	0000	0825	101	0000	0825	
	102	A2	0835	0925	0835	0945	102	0835	0945	Flight Delayed
	103	A2	1230	1400	1230	1415	103	1230	1415	Flight Delayed
	104	B2	1430	1555	1430	1555	104	1430	1555	
	161	A2	1750	1910	1800	1920	161	1800	1920	Flight Delayed
	30	B6	2015	2145	2030	2145	30	2030	2145	
	106	A2	2220	2359	2220	2359	106	2220	2359	
	34	A2	1915	2000	1915	2000				Flight Reassigned to Gate 7
3	95	B3	0020	0155	0020	0155	95	0020	0155	
	96	B7	0540	0735	0540	0735	96	0540	0735	
	86	B2	0745	0850	0745	0850	86	0745	0850	
	146	A5	0920	1030	0920	1030	146	0920	1030	
	10	B3	1035	1310	1035	1310	10	1035	1310	
	98	B3	1355	1600	1405	1615	98	1405	1615	Flight Delayed
	121	B7	1700	1910	1700	1910	121	1700	1910	
	168	B3	1925	2015	1930	2015	168	1930	2015	Flight Delayed
	12	B7	2025	2140	2035	2140	12	2035	2140	Flight Delayed
	52	B3	2145	2359	2200	2359	52	2200	2359	Flight Delayed
4	7	B7	0000	0130	0000	0130	7	0000	0130	
	129	B3	0655	0905	0655	0905	129	0655	0905	
	130	B7	0925	1055	0925	1105	130	0925	1105	Flight Delayed
	70	B7	1110	1330	1110	1335	70	1110	1335	Flight Delayed
	71	B3	1405	1720	1405	1740	71	1405	1740	Flight Delayed
	171	B3	1750	2100	1820	2140	171	1820	2140	Flight Delayed
	43	B7	2220	2359	2220	2359	43	2220	2359	
	42	A5	2130	2205	2130	2205				Flight Reassigned to Gate 8

5	62	B7	0010	0115	0010	0115	62	0010	0115	
	2	B7	0225	0855	0225	0908	2	0225	0908	Flight Delayed
	69	B7	0915	1100	0915	1115	69	0915	1115	Flight Delayed
	166	B7	1130	1315	1130	1325	166	1130	1325	Flight Delayed
	3	B7	1500	1650	1500	1650	3	1500	1650	
	19	B3	1800	2155	1830	2155	19	1830	2155	Flight Delayed
	31	B3	2205	2359	2205	2359	31	2205	2359	
6	116	A4	0240	0845	0240	0850	116	0240	0850	Flight Delayed
	76	A3	1400	1530	1400	1530	76	1400	1530	
	83	A3	1800	1920	1800	2015	83	1800	2015	Flight Delayed
	57	A3	2205	2359	2210	2359	57	2210	2359	Flight Delayed
7							34	1915	2000	
							153	0740	0945	
							54	1435	1600	
8	63	B7	0545	1030	1430	1925	63	1430	1925	
							46	0545	1030	
							42	2130	2205	
							156	2240	2359	
9	32	A3	0000	0905	0000	0905	32	0000	0905	
							137	1415	1545	
10	128	B7	2120	2359	2120	2359	128	2120	2359	
	120	B8	0630	0955	0630	1010				Flight Reassigned to Gate 11
							112	0605	0830	
							114	1210	1545	
							149	1730	1915	
11	100	B7	2115	2240	2115	2305	100	2115	2305	Flight Delayed
	112	B7	0605	0815	0605	0830				Flight Reassigned to Gate 10
							120	0630	1010	
							6	2320	2359	
12	36	A4	0000	0755	0000	0755	36	0000	0755	
	24	A4	0815	0955	0815	0955	24	0815	0955	
	92	B2	1810	1920	1815	1920	92	1815	1920	Flight Delayed
	110	A2	2000	2105	2000	2130	110	2000	2130	Flight Delayed
	35	A2	2225	2359	2230	2359	35	2230	2359	Flight Delayed
13	143	B3	0045	0240	0045	0240	143	0045	0240	
	164	B3	0700	0830	0700	0830	164	0700	0830	
	113	B7	0840	1020	0840	1055	113	0840	1055	Flight Delayed
	135	B7	1100	1215	1100	1215	135	1100	1215	

	136	A3	1245	1400	1245	1400	136	1245	1400	
	50	B7	1545	1825	1545	1825	50	1545	1825	
	4	B7	1830	2000	1830	2025	4	1830	2025	Flight Delayed
	20	B3	2140	2325	2155	2325	20	2155	2325	Flight Delayed
	21	B7	2335	2359	2335	2359	21	2335	2359	
	153	A2	1420	1540	0740	0945				Flight Reassigned to Gate 7
14	44	B8	0000	0130	0000	0130	44	0000	0130	
	157	A6	0145	0720	0145	0725	157	0145	0725	Flight Delayed
	40	B3	0745	0950	0745	1010	40	0745	1010	Flight Delayed
	59	B7	1105	1305	1105	1305	59	1105	1305	
	18	B8	1415	1515	1425	1515	18	1425	1515	Flight Delayed
	160	B7	1550	1700	1600	1735	160	1600	1735	Flight Delayed
	127	B8	1740	2030	1740	2045	127	1740	2045	Flight Delayed
	67	B3	2100	2255	2105	2330	67	2105	2330	Flight Delayed
	6	B7	2320	2359						Flight Reassigned to Gate 11
15	163	B3	0600	0755	0600	0755	163	0600	0755	
	97	B3	0815	1230	0830	1250	97	0830	1250	Flight Delayed
	108	A4	1510	1620	1510	1620	108	1510	1620	
	41	B3	1625	2050	1625	2115	41	1625	2115	Flight Delayed
	73	B3	2130	2330	2130	2330	73	2130	2330	
16	15	B7	0430	0825	0430	0825	15	0430	0825	
	152	B7	0915	1230	0915	1235	152	0915	1235	Flight Delayed
	61	B3	1915	2359	1915	2359	61	1915	2359	
	46	B3	1430	1900						Flight Reassigned to Gate 8
18	107	B2	0000	0845	0000	0845	107	0000	0845	
	87	B2	0850	1015	0850	1015	87	0850	1015	
	88	B2	1020	1125	1020	1125	88	1020	1125	
	89	B2	1215	1320	1215	1320	89	1215	1320	
	27	B2	1345	1515	1345	1515	27	1345	1515	
	138	B2	1615	1715	1615	1715	138	1615	1715	
	139	B2	1740	1825	1740	1825	139	1740	1825	
	109	B2	1845	1920	1845	1940	109	1845	1940	Flight Delayed
	93	B2	2015	2135	2015	2135	93	2015	2135	
	94	B2	2245	2359	2250	2359	94	2250	2359	Flight Delayed
19	1	A6	0000	0115	0000	0130	1	0000	0130	Flight Delayed
	8	A2	0145	0550	0145	0550	8	0145	0550	
	144	B7	0555	0650	0555	0650	144	0555	0650	
	145	B7	0710	0745	0715	0745	145	0715	0745	Flight Delayed
	9	B7	0750	0945	0750	0945	9	0750	0945	
	25	A6	0955	1045	0955	1045	25	0955	1045	

	147	B7	1050	1150	1055	1150	147	1055	1150	Flight Delayed
	26	B3	1155	1330	1215	1345	26	1215	1345	Flight Delayed
	65	B3	1540	1705	1540	1705	65	1540	1705	
	51	A6	1915	2105	1915	2130	51	1915	2130	Flight Delayed
	155	B7	2125	2215	2145	2215	155	2145	2215	Flight Delayed
	169	B3	2230	2359	2230	2359	169	2230	2359	
	137	A2	1415	1530						Flight Reassigned to Gate 9
	149	B7	1720	1850						Flight Reassigned to Gate 10
20	85	B2	0035	0650	0035	0655	85	0035	0655	Flight Delayed
	119	A2	0705	0930	0705	0945	119	0705	0945	Flight Delayed
	159	A2	1210	1515	1215	1515	159	1215	1515	Flight Delayed
	56	A4	1520	1630	1550	1630	56	1550	1630	Flight Delayed
	105	A2	1845	2035	1845	2045	105	1845	2045	Flight Delayed
	117	B2	2055	2359	2130	2359	117	2130	2359	Flight Delayed
21	74	A4	0550	0900	0550	0900	74	0550	0900	
	82	A2	1105	1515	1105	1520	82	1105	1520	Flight Delayed
	66	A2	1840	1930	1840	1930	66	1840	1930	
	141	A2	2030	2100	2030	2145	141	2030	2145	Flight Delayed
	111	A3	2215	2359	2215	2359	111	2215	2359	
22	49	B3	0000	0900	0000	0920	49	0000	0920	Flight Delayed
	60	B7	1535	1845	1535	1900	60	1535	1900	Flight Delayed
	162	B7	1950	2230	2000	2300	162	2000	2300	Flight Delayed
	165	B7	0920	1100						Flight Reassigned to Gate 27
	114	B3	1135	1525						Flight Reassigned to Gate 10
	156	B7	2240	2359						Flight Reassigned to Gate 8
23	55	A4	0205	0850	0205	0850	55	0205	0850	
	38	A2	1830	2105	1830	2105	38	1830	2105	
	84	A3	2215	2359	2215	2359	84	2215	2359	
24	118	A3	0155	0915	0155	0915	118	0155	0915	
26	58	B3	0615	0930	0615	1020	58	0615	1020	Flight Delayed
	29	B7	1705	1930	1705	1930	29	1705	1930	
	150	B3	1935	2315	1940	2330	150	1940	2330	Flight Delayed
27	68	B7	0000	0835	0000	0835	68	0000	0835	

	5	B7	2100	2300	2100	2320	5	2100	2320	Flight Delayed
							165	0920	1110	
28	151	B7	0030	0900	0030	0915	151	0030	0915	Flight Delayed
	172	B7	2205	2359	2215	2359	172	2215	2359	Flight Delayed
29	81	A3	0000	0810	0000	0810	81	0000	0810	
	37	A3	0825	1010	0825	1020	37	0825	1020	Flight Delayed
	75	A4	1205	1400	1205	1400	75	1205	1400	
	28	A2	1515	1650	1515	1650	28	1515	1650	
	33	A4	1710	1900	1710	1900	33	1710	1900	
	78	B6	1915	2100	1915	2100	78	1915	2100	
	80	A4	2245	2359	2245	2359	80	2245	2359	
30	14	B7	0000	0110	0000	0110	14	0000	0110	
	124	B3	0605	0830	0605	0845	124	0605	0845	Flight Delayed
	125	B7	0850	1030	0850	1030	125	0850	1030	
	64	B3	1125	1320	1125	1320	64	1125	1320	
	126	B3	1445	1700	1450	1705	126	1450	1705	Flight Delayed
	131	B7	1805	2000	1850	2015	131	1850	2015	Flight Delayed
	47	B7	2025	2145	2025	2145	47	2025	2145	
	13	B3	2150	2359	2150	2359	13	2150	2359	
31	22	B7	0000	0125	0000	0125	22	0000	0125	
	23	B3	0545	0815	0545	0815	23	0545	0815	
	158	B7	0825	1010	0825	1010	158	0825	1010	
	16	A6	1050	1150	1050	1150	16	1050	1150	
	17	B8	1245	1340	1245	1340	17	1245	1340	
	167	B3	1435	1715	1435	1715	167	1435	1715	
	154	B8	1755	1920	1755	1920	154	1755	1920	
	122	B7	1925	2150	1925	2150	122	1925	2150	
	48	B8	2225	2359	2225	2359	48	2225	2359	
32	39	B7	0000	0725	0000	0755	39	0000	0755	Flight Delayed
	148	B7	1230	1605	1230	1605	148	1230	1605	
	99	B3	1650	2105	1650	2105	99	1650	2105	
	132	B3	2145	2359	2155	2359	132	2155	2359	Flight Delayed
	54	A2	0740	0935						Flight Reassigned to Gate 7
33	170	B8	0655	0945	0655	1000	170	0655	1000	Flight Delayed
	11	A6	1455	1845	1500	1845	11	1500	1845	Flight Delayed
	72	A4	1910	2035	1910	2035	72	1910	2035	
	123	B8	2135	2330	2200	2350	123	2200	2350	Flight Delayed
34	45	B8	0655	1015	0655	1040	45	0655	1040	Flight Delayed
	115	B7	1850	2359	1915	2359	115	1915	2359	Flight Delayed

17	173	NIL	0000	2359	0000	2359	173	0000	2359	Gate Maintenance
11	176	NIL	0200	0400	0200	0400	176	0200	0400	Gate Maintenance
10	175	NIL	1000	1200	1000	1200	175	1000	1200	Gate Maintenance
23	177	NIL	1000	1700	1000	1700	177	1000	1700	Gate Maintenance
24	178	NIL	1000	1700	1000	1700	178	1000	1700	Gate Maintenance
12	174	NIL	1000	1700	1000	1700	174	1000	1700	Gate Maintenance
26	179	NIL	1130	1700	1130	1700	179	1130	1700	Gate Maintenance
34	180	NIL	1200	1700	1200	1700	180	1200	1700	Gate Maintenance

Appendix VI Case Study: Comparison of the Gate Recovery Results for 05:00^{am} - 10:00^{am} (No Delay Choice)

						Case 1 - Actual Delay Case of Airport and the Recovery				
GATE	Flight LEG	Aircraft Type	Expected Arrival Time	Expected Departure Time	Original Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
	101	B2	0000	0820	1	101	B2	0000	0825	1
1	102	A2	0835	0925	1	102	A2	0835	0945	1
	85	B2	0035	0650	2	85	B2	0035	0655	2
2	54	A2	0740	0935	2	54	A2	0740	0945	2
	96	B7	0540	0735	3	96	B7	0540	0735	3
	86	B2	0745	0850	3	86	B2	0745	0850	3
3	146	A5	0920	1030	3	146	A5	0920	1030	3
	124	B3	0605	0830	4	113	B7	0840	1055	4
4	113	B7	0840	1020	4					
	49	B3	0000	0900	5	49	B3	0000	0920	5
5	130	B7	0925	1055	5	130	B7	0925	1105	5
6	74	A4	0550	0900	6	74	A4	0550	0900	6
7	118	A3	0155	0915	7	118	A3	0155	0915	7
						124	B3	0605	0845	8
8										
9	55	A4	0205	0850	9	55	A4	0205	0850	9
	120	B8	0630	0955	10	157	A6	0145	0725	10
10	175	Gate Maintenance	1000	1200	10	175	B2	1000	1200	10
	151	B7	0030	0900	11	151	B7	0030	0915	11
11										
	36	A4	0000	0755	12	36	A4	0000	0755	12
12	24	A4	0815	0955	12	24	A4	0815	0955	12
	174	Gate Maintenance	1000	1700	12	174	B2	1000	1700	12
	164	B3	0700	0830	13	164	B3	0700	0830	13
13	125	B7	0850	1030	13	125	B7	0850	1030	13

14	23	B3	0545	0815	14	23	B3	0545	0815	14
	158	B7	0825	1010	14	158	B7	0825	1010	14
15	2	B7	0225	0855	15	2	B7	0225	0908	15
	152	B7	0915	1230	15	152	B7	0915	1235	15
16	58	B3	0615	0930	16	58	B3	0615	1020	16
17	68	B7	0000	0835	17	68	B7	0000	0835	17
18	107	B2	0000	0845	18	107	B2	0000	0845	18
	87	B2	0850	1015	18	87	B2	0850	1015	18
19	8	A2	0145	0550	19	8	A2	0145	0550	19
	144	B7	0555	0650	19	144	B7	0555	0650	19
	145	B7	0710	0745	19	145	B7	0715	0745	19
	9	B7	0750	0945	19	9	B7	0750	0945	19
	25	A6	0955	1045	19	25	A6	0955	1045	19
20	133	A2	0220	0600	20	133	A2	0220	0610	20
	119	A2	0705	0930	20	119	A2	0705	0945	20
21	81	A3	0000	0810	21	81	A3	0000	0810	21
	37	A3	0825	1010	21	37	A3	0825	1020	21
22	129	B3	0655	0905	22	129	B3	0655	0905	22
	69	B7	0915	1100	22	69	B7	0915	1115	22
23	116	A4	0240	0845	23	116	A4	0240	0850	23
	177	Gate Maintenance	1000	1700	23	177	B2	1000	1700	23
24	32	A3	0000	0905	24	32	A3	0000	0905	24
	178	Gate Maintenance	1000	1700	24	178	B2	1000	1700	24
25										
26	112	B7	0605	0815	26	112	B7	0605	0830	26
27	63	B7	0545	1030	27	63	B7	0545	1030	27
28	157	A6	0145	0720	28	120	B8	0630	1010	28

29	134	A2	0615	0910	29	134	A2	0615	0920	29
30	163	B3	0600	0755	30	163	B3	0600	0755	30
	97	B3	0815	1230	30	97	B3	0830	1250	30
31	39	B7	0000	0725	31	39	B7	0000	0755	8
	40	B3	0745	0950	31	40	B3	0745	1010	31
32	15	B7	0430	0825	32	15	B7	0430	0825	32
	165	B7	0920	1100	32	165	B7	0920	1110	32
33	170	B8	0655	0945	33	170	B8	0655	1000	33
34	45	B8	0655	1015	34	45	B8	0655	1040	34
Remote Stand										

(Continued)

GATE	**Case2**					**Case 3**				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**	**Flight LEG**	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	101	B2	0000	0825	1	101	B2	0000	0820	1
	102	A2	0835	0945	1	102	A2	0835	0925	1
2	85	B2	0035	0655	2	85	B2	0035	0650	2
	54	A2	0740	0945	2	54	A2	0740	0935	2
3	96	B7	0540	0735	3	96	B7	0540	0735	3
	86	B2	0745	0850	3	86	B2	0745	0850	3
	146	A5	0920	1030	3	146	A5	0920	1030	3
4	124	B3	0605	0855	4	124	B3	0605	0830	4
						113	B7	0840	1020	4
5	49	B3	0000	0920	5	49	B3	0000	0900	5
	130	B7	0925	1105	5	130	B7	0925	1055	5
6	74	A4	0550	0920	6	74	A4	0610	0900	6
7	118	A3	0155	0915	7	118	A3	0155	0915	7
8	157	A6	0145	0725	8	157	A6	0145	0720	8
	9	B7	0750	1000	8					
9	55	A4	0205	0850	9	55	A4	0205	0850	9

	23	B3	0610	0840	10					
10	175	Gate Maintenance	1000	1200	10	175	B2	1000	1200	10
	151	B7	0030	0915	11	151	B7	0030	0900	11
11										
	36	A4	0000	0755	12	36	A4	0000	0755	12
12	24	A4	0815	0955	12	24	A4	0815	0955	12
	174	Gate Maintenance	1000	1700	12	174	B2	1000	1700	12
	164	B3	0700	0830	13	164	B3	0720	0830	13
13	125	B7	0850	1030	13	125	B7	0850	1030	13
	39	B7	0000	0755	14	23	B3	0545	0815	14
14	158	B7	0825	1010	14	158	B7	0825	1010	14
	2	B7	0225	0908	15	2	B7	0225	0855	15
15	152	B7	0915	1235	15	152	B7	0915	1230	15
16	58	B3	0615	1020	16	58	B3	0615	0930	16
17	68	B7	0000	0835	17	68	B7	0000	0835	17
	113	B7	0840	1055	8					
	107	B2	0000	0845	18	107	B2	0000	0845	18
18	87	B2	0850	1015	18	87	B2	0850	1015	18
	8	A2	0145	0550	19	8	A2	0145	0550	19
	144	B7	0555	0650	19	144	B7	0555	0650	19
	145	B7	0715	0745	19	145	B7	0720	0745	19
	25	A6	0955	1045	19	9	B7	0750	0945	19
19						25	A6	0955	1045	19
	133	A2	0220	0610	20	133	A2	0220	0600	20
20	119	A2	0705	1010	20	119	A2	0705	0930	20
	81	A3	0000	0810	21	37	A3	0825	1010	21
21	37	A3	0825	1020	21					
	129	B3	0655	0905	22	129	B3	0655	0905	22
22	69	B7	0915	1115	22	69	B7	0920	1100	22
	116	A4	0240	0850	23	116	A4	0240	0845	23
23	177	Gate Maintenance	1000	1700	23	177	B2	1000	1700	23

24	32	A3	0000	0905	24	32	A3	0000	0905	24
	178	Gate Maintenance	1000	1700	24	178	B2	1000	1700	24
25						81	A3	0000	0830	25
26	112	B7	0605	0830	26	112	B7	0605	0815	26
27	63	B7	0545	1030	27	63	B7	0545	1030	27
28	120	B8	0630	1010	28	120	B8	0630	1005	28
29	134	A2	0615	0920	29	134	A2	0615	0910	29
30	163	B3	0600	0755	30	163	B3	0600	0810	30
	97	B3	0830	1250	30	97	B3	0815	1230	30
31						39	B7	0000	0725	31
	40	B3	0745	1010	31	40	B3	0745	1000	31
32	15	B7	0430	0825	32	15	B7	0600	0825	32
	165	B7	0920	1110	32	165	B7	0920	1100	32
33	170	B8	0655	1000	33	170	B8	0655	0945	33
34	45	B8	0655	1040	34	45	B8	0655	1015	34
Remote Stand										

(Continued)

GATE	Case 4					Case 5				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**	**Flight LEG**	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	101	B2	0000	0830	1	101	B2	0000	0820	1
	102	A2	0835	0925	1	102	A2	0835	0925	1
2	85	B2	0035	0650	2	85	B2	0035	0650	2
	54	A2	0740	0935	2	54	A2	0740	0935	2
3	96	B7	0540	0735	3	96	B7	0540	0735	3
	86	B2	0745	0850	3	86	B2	0810	0920	3
	146	A5	0920	1030	3	146	A5	0930	1030	3

4	124	B3	0605	0830	4	124	B3	0605	0830	4
	113	B7	0900	1100	4	113	B7	0840	1020	4
5	49	B3	0000	0900	5	49	B3	0000	0900	5
	130	B7	0925	1055	5	130	B7	0925	1055	5
6	74	A4	0550	0900	6	74	A4	0550	0900	6
7	118	A3	0155	0915	7	118	A3	0155	0915	7
8	23	B3	0615	0835	8	144	B7	0610	0720	8
	152	B7	0915	1245	8					
9	55	A4	0205	0850	9	55	A4	0205	0850	9
10	120	B8	0630	0955	10	120	B8	0630	0955	10
	175	Gate Maintenance	1000	1200	10	175	B2	1000	1200	10
11	151	B7	0030	0900	11	151	B7	0030	0900	11
12	36	A4	0000	0800	12	36	A4	0000	0755	12
						24	A4	0815	0955	12
	174	Gate Maintenance	1000	1700	12	174	B2	1000	1700	12
13	164	B3	0700	0830	13	164	B3	0700	0830	13
	125	B7	0850	1030	13	125	B7	0850	1030	13
14	158	B7	0825	1010	14	23	B3	0545	0815	14
						158	B7	0825	1010	14
15	2	B7	0225	0940	15	2	B7	0225	0855	15
						152	B7	0915	1230	15
16	58	B3	0700	0930	16	58	B3	0615	0930	16
17	68	B7	0000	0835	17	68	B7	0000	0835	17
18	107	B2	0000	0845	18	107	B2	0000	0845	18
	87	B2	0850	1015	18	87	B2	0910	1025	18
19	8	A2	0145	0550	19	8	A2	0145	0550	19
	144	B7	0555	0650	19	145	B7	0710	0745	19
	145	B7	0710	0745	19	9	B7	0750	0945	19

	9	B7	0750	0945	19	25	A6	0955	1045	19
	25	A6	0955	1045	19					
20	133	A2	0220	0600	20	133	A2	0220	0600	20
	119	A2	0705	0930	20	119	A2	0705	0930	20
21	81	A3	0000	0810	21	81	A3	0000	0810	21
	37	A3	0825	1010	21	37	A3	0825	1010	21
22	129	B3	0655	0905	22	129	B3	0700	0905	22
	69	B7	0915	1100	22	69	B7	0915	1100	22
23	116	A4	0240	0845	23	116	A4	0240	0845	23
	177	Gate Maintenance	1000	1700	23	177	B2	1000	1700	23
24	32	A3	0000	0905	24	32	A3	0000	0905	24
	178	Gate Maintenance	1000	1700	24	178	B2	1000	1700	24
25	24	A4	0815	10000	25					
26	112	B7	0605	0845	26	112	B7	0700	0900	26
27	63	B7	0545	1030	27	63	B7	0545	1030	27
28	157	A6	0145	0720	28	157	A6	0145	0755	28
29	134	A2	0615	0910	29	134	A2	0615	0910	29
30	163	B3	0600	0755	30	163	B3	0600	0755	30
	97	B3	0815	1230	30	97	B3	0815	1230	30
31	39	B7	0000	0725	31	39	B7	0000	0725	31
	40	B3	0745	0950	31	40	B3	0745	0950	31
32	15	B7	0430	0825	32	15	B7	0500	0830	32
	165	B7	0920	1100	32	165	B7	0920	1100	32
33	170	B8	0715	0955	33	170	B8	0655	0945	33
34	45	B8	0655	1015	34	45	B8	0655	1035	34
Remote Stand										

(Continued)

GATE	Case 6					Case 7				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**	**Flight LEG**	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	101	B2	0000	0820	1	101	B2	0000	0825	1
	102	A2	0835	0925	1	102	A2	0835	0945	1
2	85	B2	0345	0650	2	85	B2	0035	0650	2
	54	A2	0740	0945	2	54	A2	0740	0945	2
3	96	B7	0540	0735	3	96	B7	0540	0735	3
	86	B2	0745	0850	3	86	B2	0745	0850	3
	146	A5	0920	1030	3	146	A5	0920	1030	3
4	124	B3	0615	0815	4	145	B7	0715	0830	4
	113	B7	0840	1020	4	113	B7	0840	1040	4
5	49	B3	0000	0920	5	49	B3	0000	0920	5
	130	B7	0925	1055	5	130	B7	0925	1100	5
6	74	A4	0550	0900	6	74	A4	0550	0900	6
7	118	A3	0155	0915	7	118	A3	0155	0915	7
8						39	B7	0000	0755	**8**
9	55	A4	0205	0850	9	55	A4	0205	0850	9
10	120	B8	0630	0955	10	124	B3	0605	0845	10
	175	Gate Maintenance	1000	1200	10	175	B2	1000	1200	10
11	151	B7	0030	0900	11	151	B7	0030	0910	11
12	36	A4	0000	0755	12	36	A4	0000	0755	12
	24	A4	0815	0955	12	24	A4	0815	0955	12
	174	Gate Maintenance	1000	1700	12	174	B2	1000	1700	12
13	164	B3	0700	0830	13	164	B3	0700	0830	13
	125	B7	0850	1030	13	125	B7	0850	1030	13
14	23	B3	0545	0815	14	23	B3	0545	0815	14
	158	B7	0825	1010	14	158	B7	0825	1010	14

15	2	B7	0225	0855	15	2	B7	0225	0855	15
	152	B7	0915	1310	15	152	B7	0915	1300	15
16	58	B3	0615	0930	16	58	B3	0615	0950	16
17	68	B7	0000	0835	17	68	B7	0000	0835	17
18	107	B2	0000	0845	18	107	B2	0000	0845	18
	87	B2	0850	1015	18	87	B2	0850	1015	18
19	8	A2	0145	0550	19	8	A2	0145	0550	19
	144	B7	0555	0650	19	144	B7	0555	0650	19
	145	B7	0710	0745	19	9		0750	0945	19
	9	B7	0750	0945	19	25	B7	0955	1045	19
	25	A6	1000	1120	19		A6			
20	133	A2	0330	0635	20	133	A2	0450	0610	20
	119	A2	0705	0930	20	119	A2	0705	0945	20
21	81	A3	0000	0810	21	81	A3	0000	0820	21
	37	A3	0825	1020	21	37	A3	0825	1020	21
22	129	B3	0655	0905	22	129	B3	0655	0905	22
	69	B7	0920	1100	22	69	B7	0915	1100	22
23	116	A4	0240	0845	23	116	A4	0240	0845	23
	177	Gate Maintenance	1000	1700	23	177	B2	1000	1700	23
24	32	A3	0000	0905	24	32	A3	0000	0905	24
	178	Gate Maintenance	1000	1700	24	178	B2	1000	1700	24
25										
26	112	B7	0605	0820	26	112	B7	0605	0835	26
27	63	B7	0545	1030	27	63	B7	0600	1055	27
28	157	A6	0145	0720	28	120	B8	0630	1010	28
29	134	A2	0615	0910	29	134	A2	0615	0920	29

30	163	B3	0600	0755	30	163	B3	0600	0755	30
	97	B3	0815	1230	30	97	B3	0830	1250	30
31	39	B7	0000	0725	31	157	A6	0145	0725	31
	40	B3	0745	0955	31	40	B3	0745	1010	31
32	15	B7	0430	0825	32	15	B7	0510	0825	32
	165	B7	0920	1100	32	165	B7	0920	1100	32
33	170	B8	0655	0950	33	170	B8	0655	1000	33
34	45	B8	0655	1015	34	45	B8	0655	1040	34
Remote Stand										

(Continued)

GATE	Case 8					Case 9				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**	**Flight LEG**	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	101	B2	0000	0830	1	101	B2	0000	0825	1
	102	A2	0835	0945	1	102	A2	0835	0945	1
2	85	B2	0035	0650	2	85	B2	0035	0650	2
	54	A2	0740	0945	2	54	A2	0740	0945	2
3	96	B7	0540	0735	3	164	B3	0630	0830	3
	86	B2	0750	0850	3	146	A5	0900	1030	3
	146	A5	0920	1030	3					
4	124	B3	0605	0815	4	39	B7	0000	0755	4
	113	B7	0840	1040	4	113	B7	0840	1040	4
5	49	B3	0000	0920	5	49	B3	0000	0920	5
	130	B7	0930	1100	5	130	B7	0925	1100	5
6	74	A4	0550	0900	6	74	A4	0550	0900	6
7	118	A3	0155	0915	7	118	A3	0155	0915	7
8	157	A6	0145	0725	8	23	B3	0545	0825	8
	152	B7	0915	1300	8	152	B7	0915	1300	8
9	55	A4	0425	0850	9	55	A4	0205	0850	9
10	145	B7	0715	0830	10	124	B3	0605	0845	10

	175	Gate Maintenance	1000	1200	10	175	B2	1000	1200	10
	151	B7	0030	0910	11	151	B7	0030	0910	11
11										
	36	A4	0000	0755	12	36	A4	0000	0755	12
12	24	A4	0815	0955	12	24	A4	0815	0955	12
	174	Gate Maintenance	1000	1700	12	174	B2	1000	1700	12
	164	B3	0700	0830	13	96	B7	0540	0740	13
13	125	B7	0850	1030	13	125	B7	0755	1030	13
	23	B3	0545	0815	14					
14	158	B7	0825	1010	14	158	B7	0755	1010	14
	2	B7	0225	0915	15	2	B7	0225	0915	15
15										
16	58	B3	0615	1000	16	58	B3	0615	0950	16
17	68	B7	0000	0835	17	68	B7	0000	0835	17
	107	B2	0000	0845	18	107	B2	0000	0845	18
18	87	B2	0850	1015	18	87	B2	0850	1015	18
	8	A2	0145	0550	19	8	A2	0145	0550	19
	144	B7	0555	0650	19	144	B7	0555	0650	19
	9	B7	0750	0950	19	145	B7	0715	0830	19
	25	A6	0955	1045	19	25	A6	0955	1045	19
19										
	133	A2	0450	0610	20	133	A2	0450	0610	20
20	119	A2	0705	0950	20	119	A2	0655	0950	20
	81	A3	0000	0810	21	81	A3	0000	0820	21
21	37	A3	0825	1045	21	37	A3	0825	1035	21
	129	B3	0655	0905	22	129	B3	0655	0905	22
22	69	B7	10000	1100	22	69	B7	0915	1100	22
	116	A4	0240	0845	23	116	A4	0240	0855	23
23	177	Gate Maintenance	1000	1700	23	177	B2	1000	1700	23
24	32	A3	0000	0905	24	32	A3	0000	0905	24

	178	Gate Maintenance	1000	1700	24	178	B2	1000	1700	24
25						86	B2	0745	0910	25
26	112	B7	0605	0900	26	112	B7	0555	0835	26
27	63	B7	0600	1030	27	63	B7	0600	1055	27
28	120	B8	0630	1010	28	157	A6	0145	0725	28
						9	B7	0750	0950	28
29	134	A2	0615	0910	29	134	A2	0615	0920	29
30	163	B3	0600	0755	30	163	B3	0600	0755	30
	97	B3	0830	1230	30	97	B3	0830	1250	30
31	39	B7	0000	0730	31					
	40	B3	0745	1010	31	40	B3	0745	1010	31
32	15	B7	0510	0825	32	15	B7	0510	0825	32
	165	B7	0920	1100	32	165	B7	0920	1100	32
33	170	B8	0655	1015	33	170	B8	0655	1015	33
34	45	B8	0655	1040	34	45	B8	0655	1045	34
Remote Stand						120	B8	0630	1020	Remote

(Continued)

GATE	**Case 10**				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	101	B2	0000	0825	1
	102	A2	0835	0945	1
2	85	B2	0035	0650	2
	54	A2	0740	0945	2
3	86	B2	0730	0845	3
	146	A5	0900	1030	3
4	124	B3	0605	0845	4
	69	B7	0855	1045	4

5	49	B3	0000	0920	5
	130	B7	0925	1100	5
6	74	A4	0550	0900	6
7	118	A3	0155	0915	7
8	23	B3	0545	0820	8
	113	B7	0840	1040	8
9	55	A4	0205	0850	9
10	164	B3	0630	0830	10
	175	Gate Maintenance	1000	1200	10
11	151	B7	0030	0910	11
	152	B7	0915	1300	11
12	36	A4	0000	0755	12
	24	A4	0820	0955	12
	174	Gate Maintenance	1000	1700	12
13	96	B7	0540	0745	13
	125	B7	0755	1030	13
14	158	B7	0755	1010	14
15	2	B7	0225	0915	15
16	58	B3	0615	0950	16
17	68	B7	0000	0835	17
18	107	B2	0000	0845	18
	87	B2	0850	1015	18
19	8	A2	0145	0550	19
	144	B7	0600	0650	19
	145	B7	0715	0830	19
	25	A6	0920	1020	19

	133	A2	0450	0610	20
20	119	A2	0655	0950	20
	81	A3	0000	0820	21
21	37	A3	0825	1035	21
	129	B3	0655	0905	22
22					
	116	A4	0240	0855	23
23	177	Gate Maintenance	1000	1700	23
	32	A3	0000	0905	24
24	178	Gate Maintenance	1000	1700	24
25					
26	112	B7	0555	0835	26
27	63	B7	0600	1055	27
	157	A6	0145	0725	28
28	9	B7	0750	0950	28
29	134	A2	0615	0920	29
	163	B3	0600	0755	30
30	97	B3	0830	1250	30
31	40	B3	0745	1010	31
	15	B7	0510	0825	32
32	165	B7	0920	1100	32
33	170	B8	0655	1015	33
34	45	B8	0655	1040	34
Remote Stand	39	B7	0000	0755	Remote
	120	B8	0630	1025	Remote

Gate Maintenance

Reassigned Flight

Appendix VII Case Study: Comparison of the Gate Recovery Results for 10:00^{am} - 19:00^{am} (No Delay Choice)

	Non-Peak Hour: 10:00 -- 19:00					Case 1-Actual Airport Delay Case				
GATE	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Original Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
	90	B2	1225	1500	1	90	B2	1225	1500	1
	91	B2	1515	1630	1	91	B2	1515	1630	1
	77	A3	1705	1855	1	77	A3	1705	1855	1
1	140	B2	1900	2015	1	140	B2	1900	2015	1
	103	A2	1230	1400	2	103	A2	1230	1415	2
	104	B2	1430	1555	2	104	B2	1430	1555	2
2	161	A2	1750	1910	2	161	A2	1800	1920	2
	146	A5	0920	1030	3	146	A5	0920	1030	3
	10	B3	1035	1310	3	10	B3	1035	1310	3
	98	B3	1355	1600	3	98	B3	1405	1615	3
3	121	B7	1700	1910	3	121	B7	1700	1910	3
	130	B7	0925	1055	4	130	B7	0925	1105	4
	70	B7	1110	1330	4	70	B7	1110	1335	4
	71	B3	1405	1720	4	71	B3	1405	1740	4
4	171	B3	1750	2100	4	171	B3	1820	2140	4
	69	B7	0915	1100	5	69	B7	0915	1115	5
	166	B7	1130	1315	5	166	B7	1130	1325	5
	3	B7	1500	1650	5	3	B7	1500	1650	5
5	19	B3	1800	2155	5	19	B3	1830	2155	5
	76	A3	1400	1530	6	76	A3	1400	1530	6
	83	A3	1800	1920	6	83	A3	1800	2015	6
6										
						153	A2	1435	1600	7
7										
	63	B7	0545	1030	8	63	B7	0545	1030	8
						114	B3	1210	1545	8
8										
						137	A2	1415	1545	9
9										

	175	B2	1000	1200	10	175	B2	1000	1200	10
10										
11										
	174	B2	1000	1700	12	174	B2	1000	1700	12
12	92	B2	1810	1920		92	B2	1815	1920	12
	113	B7	0840	1020	13	113	B7	0840	1055	13
	135	B7	1100	1215	13	135	B7	1100	1215	13
	136	A3	1245	1400	13	136	A3	1245	1400	13
	153	A2	1420	1540	13	50	B7	1545	1825	13
	50	B7	1545	1825	13	4	B7	1830	2025	13
13	4	B7	1830	2000	13					
	59	B7	1105	1305	14	59	B7	1105	1305	14
	18	B8	1415	1515	14	18	B8	1425	1515	14
	160	B7	1550	1700	14	160	B7	1600	1735	14
14	127	B8	1740	2030	14	127	B8	1740	2045	14
	97	B3	0815	1230	15	97	B3	0830	1250	15
	108	A4	1510	1620	15	108	A4	1510	1620	15
15	41	B3	1625	2050	15	41	B3	1625	2115	15
	152	B7	0915	1230	16	152	B7	0915	1235	16
16	46	B3	1430	1900	16	46	B3	1430	1925	16
17										
	87	B2	0850	1015	18	87	B2	0850	1015	18
	88	B2	1020	1125	18	88	B2	1020	1125	18
	89	B2	1215	1320	18	89	B2	1215	1320	18
	27	B2	1345	1515	18	27	B2	1345	1515	18
	138	B2	1615	1715	18	138	B2	1615	1715	18
	139	B2	1740	1825	18	139	B2	1740	1825	18
18	109	B2	1845	1920	18	109	B2	1845	1940	18
	25	A6	0955	1045	19	25	A6	0955	1045	19
	147	B7	1050	1150	19	147	B7	1055	1150	19
	26	B3	1155	1330	19	26	B3	1215	1345	19
	137	A2	1415	1530	19	65	B3	1540	1705	19
19	65	B3	1540	1705	19	149	B7	1730	1915	19
	149	B7	1720	1850	19					
20										
	159	A2	1210	1515	20	159	A2	1215	1515	20
	56	A4	1520	1630	20	56	A4	1550	1630	20

	105	A2	1845	2035	20	105	A2	1845	2045	20
	82	A2	1105	1515	21	82	A2	1105	1520	21
21	66	A2	1840	1930	21	66	A2	1840	1930	21
	165	B7	0920	1100	22					
	114	B3	1135	1525	22	165	B7	0920	1110	22
22	60	B7	1535	1845	22	60	B7	1535	1900	22
	177	B2	1000	1700	23	177	B2	1000	1700	23
23	38	A2	1830	2105	23	38	A2	1830	2105	23
24	178	B2	1000	1700	24	178	B2	1000	1700	24
25										
	179	B2	1130	1700	26	179	B2	1130	1700	26
26	29	B7	1705	1930		29	B7	1705	1930	26
27										
28										
	37	A3	0825	1010	29	37	A3	0825	1020	29
	75	A4	1205	1400	29	75	A4	1205	1400	29
	28	A2	1515	1650	29	28	A2	1515	1650	29
29	33	A4	1710	1900	29	33	A4	1710	1900	29
	125	B7	0850	1030	30	125	B7	0850	1030	30
	64	B3	1125	1320	30	64	B3	1125	1320	30
	126	B3	1445	1700	30	126	B3	1450	1705	30
30	131	B7	1805	2000	30	131	B7	1850	2015	30
	158	B7	0825	1010	31	158	B7	0825	1010	31
	16	A6	1050	1150	31	16	A6	1050	1150	31
	17	B8	1245	1340	31	17	B8	1245	1340	31
	167	B3	1435	1715	31	167	B3	1435	1715	31
31	154	B8	1755	1920	31	154	B8	1755	1920	31
	148	B7	1230	1605	32	148	B7	1230	1605	32
32	99	B3	1650	2105	32	99	B3	1650	2105	32
33	11	A6	1455	1845	33	11	A6	1500	1845	33
	45	B8	0655	1015	34	45	B8	0655	1040	34
	115	B7	1850	2359	34	115	B7	1915	2359	34
34	180	B2	1200	1700	34	180	B2	1200	1700	34

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GATE	Case 2					Case 3				
	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
1	90	B2	1225	1500	1	90	B2	1225	1500	1
	91	B2	1515	1630	1	91	B2	1515	1630	1
	77	A3	1705	1855	1	77	A3	1705	1855	1
	140	B2	1900	2015	1	140	B2	1900	2015	1
2	103	A2	1230	1400	2	103	A2	1230	1400	2
	104	B2	1520	1420	2	104	B2	1430	1555	2
	161	A2	1800	1910	2	161	A2	1750	1910	2
3	146	A5	0920	1030	3	146	A5	0920	1030	3
	10	B3	1035	1310	3	10	B3	1035	1310	3
	98	B3	1400	1610	3	98	B3	1355	1600	3
	121	B7	1700	1910	3	121	B7	1700	1910	3
4	130	B7	0925	1055	4	130	B7	0925	1055	4
	70	B7	1110	1400	4	70	B7	1110	1330	4
	71	B3	1405	1720	4	71	B3	1405	1720	4
	171	B3	1800	2100	4	171	B3	1750	2035	4
5	69	B7	0915	1100	5	69	B7	0915	1100	5
	166	B7	1130	1315	5	165	B7	1150	1430	5
	3	B7	1500	1650	5	3	B7	1500	1650	5
	19	B3	1800	2155	5	19	B3	1800	2155	5
6	76	A3	1400	1530	6	76	A3	1400	1530	6
	83	A3	1800	1920	6	83	A3	1800	1920	6
7	137	A2	1415	1600	7					
8	63	B7	0545	1030	8	63	B7	0545	1030	8
	147	B7	1045	1150	8	166	B7	1225	1500	8
	136	A3	1245	1455	8					
9						108	A4	1510	1625	9
						89	B2	1245	1455	9
10	175	B2	1000	1200	10	175	B2	1000	1200	10
						17	B8	1345	1540	10

11										
	174	B2	1000	1700	12	174	B2	1000	1700	12
12	92	B2	1810	1920	12	92	B2	1810	1920	12
	113	B7	0840	1020	13	113	B7	0840	1020	13
	135	B7	1100	1215	13	135	B7	1100	1215	13
	153	A2	1420	1540	13	136	A3	1245	1400	13
	50	B7	1545	1825	13	153	A2	1420	1540	13
	4	B7	1830	2000	13	50	B7	1545	1825	13
13						4	B7	1830	2000	13
	59	B7	1105	1305	14	59	B7	1105	1305	14
	18	B8	1415	1515	14	18	B8	1415	1515	14
	160	B7	1555	1700	14	160	B7	1600	1700	14
14	127	B8	1740	2030	14	127	B8	1740	2030	14
	97	B3	0815	1230	15	97	B3	0905	1230	15
	108	A4	1510	1620	15	41	B3	1625	2050	15
15	41	B3	1625	2100	15					
	152	B7	0915	1230	16	152	B7	0915	1230	16
16	46	B3	1430	1900	16	46	B3	1430	1920	16
17										
	87	B2	0850	1015	18	87	B2	0900	1015	18
	88	B2	1020	1125	18	88	B2	1035	1220	18
	89	B2	1215	1320	18	27	B2	1345	1515	18
	27	B2	1420	1600	18	138	B2	1615	1715	18
	138	B2	1615	1715	18	139	B2	1740	1825	18
	139	B2	1740	1825	18	109	B2	1845	1940	18
18	109	B2	1845	1920	18					
	25	A6	1000	1110	19	25	A6	0955	1045	19
	26	B3	1210	1330	19	147	B7	1050	1150	19
	65	B3	1540	1705	19	26	B3	1155	1330	19
	149	B7	1750	1900	19	137	A2	1415	1530	19
19						65	B3	1540	1705	19
						149	B7	1720	1850	19
	159	A2	1220	1515	20	159	A2	1210	1515	20
	56	A4	1530	1630	20	56	A4	1525	1630	20
20	105	A2	1845	2035	20	105	A2	1845	2035	20

	82	A2	1105	1520	21	82	A2	1105	1515	21
21	66	A2	1840	1930	21	66	A2	1840	1930	21
	165	B7	0920	1100	22	114	B3	1135	1525	22
	114	B3	1135	1525	22	60	B7	1535	1845	22
22	60	B7	1535	1850	22					
	177	B2	1000	1700	23	177	B2	1000	1700	23
23	38	A2	1830	2105	23	38	A2	1830	2105	23
24	178	B2	1000	1700	24	178	B2	1000	1700	24
25										
	179	B2	1130	1700	26	179	B2	1130	1700	26
26	29	B7	1705	1930	26	29	B7	1705	1930	26
27										
28										
	37	A3	0825	1010	29	37	A3	0825	1050	29
	75	A4	1205	1400	29	75	A4	1205	1400	29
	28	A2	1515	1650	29	28	A2	1515	1650	29
29	33	A4	1710	1900	29	33	A4	1710	1900	29
	125	B7	0850	1030	30	125	B7	0850	1030	30
	64	B3	1125	1320	30	64	B3	1125	1410	30
	126	B3	1445	1700	30	126	B3	1445	1710	30
30	131	B7	1805	2000	30	131	B7	1805	2000	30
	158	B7	0825	1010	31	158	B7	0825	1010	31
	16	A6	1050	12:30	31	16	A6	1110	1230	31
	17	B8	1320	1340	31	167	B3	1435	1715	31
	167	B3	1435	1715	31	154	B8	1755	1920	31
31	154	B8	1755	1920	31					
	148	B7	1230	1605	32	148	B7	1310	1605	32
32	99	B3	1650	2105	32	99	B3	1650	2105	32
33	11	A6	1455	1845	33	11	A6	1500	1845	33
	45	B8	0655	1015	34	45	B8	0655	1030	34
	115	B7	1850	2359	34	115	B7	1900	2359	34
34	180	B2	1200	1700	34	180	B2	1200	1700	34

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GATE	Case 4					Case 5				
	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
	90	B2	1225	1500	1	90	B2	1225	1500	1
	91	B2	1515	1630	1	91	B2	1515	1630	1
	77	A3	1705	1855	1	77	A3	1705	1855	1
1	140	B2	1900	2015	1	140	B2	1900	2015	1
	103	A2	1300	1500	2	103	A2	1230	1430	2
	108	A4	1510	1655	2	161	A2	1750	1910	2
2	161	A2	1750	1910	2					
	10	B3	1035	1310	3	146	A5	0920	1030	3
	98	B3	1355	1600	3	98	B3	1355	1600	3
	121	B7	1700	1910	3	121	B7	1700	1910	3
3										
	130	B7	0925	1100	4	130	B7	0925	1055	4
	70	B7	1110	1400	4	70	B7	1110	1330	4
	71	B3	1405	1720	4	71	B3	1405	1720	4
4	171	B3	1750	2100	4	171	B3	1750	2100	4
	69	B7	0915	1100	5	69	B7	0915	1100	5
	166	B7	1130	1320	5	166	B7	1130	1355	5
	3	B7	1500	1650	5	3	B7	1500	1650	5
5	19	B3	1800	2155	5	19	B3	1810	2155	5
	76	A3	1400	1530	6	89	A3	1215	1320	6
	83	A3	1800	1920	6	76	A3	1400	1530	6
6						83		1800	1920	6
	89	B2	1220	1420	7	136	A3	1245	1425	7
	104	B2	1435	1555	7	104	B2	1430	1605	7
7	139	B2	1740	1845	7					
	63	B7	0545	1100	8	63	B7	0545	1030	8
						25	A6	1055	1500	8
8										
						137	A2	1415	1540	9
9										
	175	B2	1000	1200	10	175	B2	1000	1200	10
10										

11	146	A5	0920	1120	11	165	B7	0920	1200	11
	174	B2	1000	1700	12	174	B2	1000	1700	12
12	92	B2	1810	1920	12	92	B2	1810	1920	12
	113	B7	0840	1020	13	113	B7	0840	1020	13
	135	B7	1100	1215	13	135	B7	1100	1215	13
	136	A3	1245	1415	13	153	A2	1425	1540	13
	153	A2	1425	1540	13	50	B7	1545	1825	13
	50	B7	1545	1825	13	4	B7	1830	2000	13
13	4	B7	1830	2000	13					
	59	B7	1105	1305	14	59	B7	1105	1410	14
	18	B8	1420	1515	14	18	B8	1420	1530	14
	160	B7	1550	1700	14	160	B7	1610	1700	14
14	127	B8	1740	2030	14	127	B8	1740	2030	14
	97	B3	0815	1230	15	97	B3	0815	1245	15
	41	B3	1625	2050	15	108	A4	1510	1620	15
15						41	B3	1625	2050	15
	152	B7	0915	1330	16	152	B7	0915	1230	16
16	46	B3	1430	1900	16	46	B3	1430	1910	16
17						10	B3	1055	1400	17
	87	B2	0850	1015	18	87	B2	0850	1015	18
	88	B2	1020	1320	18	88	B2	1020	1330	18
	27	B2	1345	1535	18	27	B2	1345	1515	18
	138	B2	1625	1715	18	138	B2	1615	1715	18
	109	B2	1845	1920	18	139	B2	1740	1825	18
						109	B2	1845	1930	18
18							B2			
	25	A6	0955	1045	19	147		1050	1150	19
	147	B7	1055	1150	19	26	B7	1155	1420	19
	26	B3	1155	1330	19	65	B3	1540	1705	19
	137	A2	1415	1530	19	149		1725	1850	19
19	65	B3	1540	1705	19		B3			
	149	B7	1720	1850	19		B7			
	159	A2	1210	1515	20	159	A2	1210	1515	20
	56	A4	1520	1630	20	56	A4	1540	1630	20
20	105	A2	1845	2035	20	105	A2	1845	2035	20
	82	A2	1210	1525	21	82	A2	1110	1555	21
21	66	A2	1840	1930	21	66	A2	1840	1930	21

	165	B7	0920	1100	22	114	B3	1135	1525	22
	114	B3	1135	1525	22	60	B7	1535	1900	22
22	60	B7	1535	1845	22					
	177	B2	1000	1700	23	177	B2	1000	1700	23
23	38	A2	1830	2105	23	38	A2	1830	2105	23
24	178	B2	1000	1700	24	178	B2	1000	1700	24
25										
	179	B2	1130	1700	26	179	B2	1130	1700	26
26	29	B7	1705	1930	26	29	B7	1705	1930	26
27										
28										
	37	A3	0825	1010	29	37	A3	0825	1010	29
	75	A4	1205	1400	29	75	A4	1205	1400	29
	28	A2	1515	1650	29	28	A2	1515	1650	29
29	33	A4	1710	1900	29	33	A4	1710	1900	29
	125	B7	0850	1030	30	125	B7	0950	1300	30
	64	B3	1125	1320	30	64	B3	1125	1320	3
	126	B3	1445	1700	30	126	B3	1450	1700	30
30	131	B7	1805	2000	30	131	B7	1805	2000	30
	158	B7	0825	1010	31	158	B7	0825	1010	31
	16	A6	1050	1215	31	16	A6	1050	1150	31
	17	B8	1245	1410	31	17	B8	1300	1420	31
	167	B3	1435	1715	31	167	B3	1435	1715	31
31	154	B8	1755	1920	31	154	B8	1755	1920	31
	148	B7	1230	1605	32	148	B7	1230	1605	32
32	99	B3	1650	2105	32	99	B3	1650	2105	32
33	11	A6	1455	1845	33	11	A6	1455	1845	33
	45	B8	0655	1015	34	45	B8	0655	1015	34
	115	B7	1850	2359	34	115	B7	1855	2359	34
34	180	B2	1200	1700	34	180	B2	1200	1700	34

Appendix VIII Case Study: Comparison of the Gate Recovery Results for 19:00^{am} - 23:59^{am} (No Delay Choice)

GATE	Peak Hours 19:00 --- 23:59					Case 1 - Actual Airport Delay Case				
	Flight LEG	Aircraft Type	Expected Arrival Time	Expected Departure Time	Original Optimal Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
1	140	B2	1900	2015	1	140	B2	1900	2015	1
1	79	A4	2055	2245	1	79	A4	2100	2245	1
1	142	B2	2320	2359	1	142	B2	2320	2359	1
2	161	A2	1750	1910	2	34	A2	1915	2000	2
2	34	A2	1915	2000	2	30	B6	2030	2145	2
2	30	B6	2015	2145	2	106	A2	2220	2359	2
2	106	A2	2220	2359	2					
3	121	B7	1700	1910	3	121	B7	1700	1910	3
3	168	B3	1925	2015	3	168	B3	1930	2015	3
3	12	B7	2025	2140	3	12	B7	2035	2140	3
3	52	B3	2145	2359	3	52	B3	2200	2359	3
4	171	B3	1750	2100	4	42	A5	2130	2205	4
4	42	A5	2130	2205	4	43	B7	2220	2359	4
4	43	B7	2220	2359	4					
5	19	B3	1800	2155	5	19	B3	1830	2155	5
5	31	B3	2205	2359	5	31	B3	2205	2359	5
6	83	A3	1800	1920	6	83	A3	1800	2015	6
6	57	A3	2205	2359	6	57	A3	2210	2359	6
7						161	A2	1800	1920	7
						162	B7	2000	2300	7
8						171	B3	1820	2140	8
9						67	B3	2105	2330	9
10	128	B7	2120	2359	10	128	B7	2120	2359	10
11	100	B7	2115	2240	11	100	B7	2115	2305	11

12	92	B2	1810	1920	12	92	B2	1815	1920	12
12	110	A2	2000	2105	12	110	A2	2000	2130	12
12	35	A2	2225	2359	12	35	A2	2230	2359	12
13	4	B7	1830	2000	13	4	B7	1830	2025	13
13	20	B3	2140	2325	13	20	B3	2155	2325	13
13	21	B7	2335	2359	13	21	B7	2335	2359	13
14	127	B8	1740	2030	14	127	B8	1740	2045	14
14	67	B3	2100	2255	14	6	B7	2320	2359	14
14	6	B7	2320	2359	14					
15	41	B3	1625	2050	15	41	B3	1625	2115	15
15	73	B3	2130	2330	15	73	B3	2130	2330	15
16	61	B3	1915	2359	16	61	B3	1915	2359	16
17	173	B2	0000	2359	17	173	B2	0000	2359	17
18	109	B2	1845	1920	18	109	B2	1845	1940	18
18	93	B2	2015	2135	18	93	B2	2015	2135	18
18	94	B2	2245	2359	18	94	B2	2250	2359	18
19	51	A6	1915	2105	19	51	A6	1915	2130	19
19	155	B7	2125	2215	19	155	B7	2145	2215	19
19	169	B3	2230	2359	19	169	B3	2230	2359	19
20	105	A2	1845	2035	20	105	A2	1845	2045	20
20	117	B2	2055	2359	20	117	B2	2130	2359	20
21	66	A2	1840	1930	21	66	A2	1840	1930	21
21	141	A2	2030	2100	21	141	A2	2030	2145	21
21	111	A3	2215	2359	21	111	A3	2215	2359	21
22	162	B7	1950	2230	22	156	B7	2240	2359	22
22	156	B7	2240	2359	22					
23	38	A2	1830	2105	23	38	A2	1830	2105	23
23	84	A3	2215	2359	23	84	A3	2215	2359	23
24										
25										
26	29	B7	1705	1930	26	29	B7	1705	1930	26
26	150	B3	1935	2315	26	150	B3	1940	2330	26
27	5	B7	2100	2300	27	5	B7	2100	2320	27

28	172	B7	2205	2359	28	172	B7	2215	2359	28
29	78	B6	1915	2100	29	78	B6	1915	2100	29
29	80	A4	2245	2359	29	80	A4	2245	2359	29
30	131	B7	1805	2000	30	131	B7	1850	2015	30
30	47	B7	2025	2145	30	47	B7	2025	2145	30
30	13	B3	2150	2359	30	13	B3	2150	2359	30
31	154	B8	1755	1920	31	154	B8	1755	1920	31
31	122	B7	1925	2150	31	122	B7	1925	2150	31
31	48	B8	2225	2359	31	48	B8	2225	2359	31
32	99	B3	1650	2105	32	99	B3	1650	2105	32
32	132	B3	2145	2359	32	132	B3	2155	2359	32
33	72	A4	1910	2035	33	72	A4	1910	2035	33
33	123	B8	2135	2330	33	123	B8	2200	2350	33
34	115	B7	1850	2359	34	115	B7	1915	2359	34
Remote Stand										

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GATE	**Case 2**					**Case 3**				
	Flight LEG	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**	**Flight LEG**	**Aircraft Type**	**Actual Arrival Time**	**Actual Departure Time**	**Recovery Assignment**
1	140	B2	1900	2015	1	140	B2	1920	2050	1
1	79	A4	2055	2245	1	79	A4	2110	2245	1
1	142	B2	2320	2359	1	142	B2	2320	2359	1
2	161	A2	1750	1910	2	161	A2	1750	1910	2
2	34	A2	1925	2000	2	30	B6	2020	2145	2
2	30	B6	2015	2145	2	106	A2	2220	2359	2
2	106	A2	2220	2359	2					
3	168	B3	1925	2015	3	121	B7	1700	1910	3
3	12	B7	2025	2140	3	168	B3	1925	2015	3
3	52	B3	2150	2359	3	12	B7	2025	2140	3
3						52	B3	2145	2359	3
4	171	B3	1750	2100	4	171	B3	1755	2100	4
4	42	A5	2130	2230	4	43	B7	2220	2359	4
4										

5	19	B3	1800	2155	5	19	B3	1800	2220	5
5	31	B3	2205	2359	5					
6	83	A3	1800	1945	6	83	A3	1800	1920	6
6	57	A3	2210	2359	6	34	A2	1930	2040	6
						57	A3	2205	2359	6
7						42	A5	2130	2235	7
8	121	B7	1800	1945	8	31	B3	2220	2359	8
	47	B7	2025	2200	8					
	43	B7	2230	2359	8					
9						99	B3	1730	2155	9
10	128	B7	2120	2359	10	128	B7	2120	2359	10
11	100	B7	2115	2245	11	100	B7	2115	2245	11
12	92	B2	1815	1920	12	92	B2	1810	1920	12
12	110	A2	2000	2105	12	110	A2	2000	2105	12
12	35	A2	2225	2359	12	35	A2	2225	2359	12
13	4	B7	1830	2020	13	4	B7	1830	2015	13
13	20	B3	2140	2325	13	20	B3	2140	2325	13
13	21	B7	2335	2359	13	21	B7	2335	2359	13
14	127	B8	1800	2030	14	127	B8	1740	2105	14
14	67	B3	2100	2255	14	67	B3	2120	2255	14
14	6	B7	2320	2359	14	6	B7	2320	2359	14
15	41	B3	1625	2050	15	41	B3	1625	2050	15
15	73	B3	2130	2330	15	73	B3	2130	2330	15
16	61	B3	1915	2359	16	61	B3	1915	2359	16
17	173	B2	0000	2359	17	173	B2	0000	2359	17
18	109	B2	1900	2010	18	109	B2	1845	1920	18
18	93	B2	2015	2135	18	93	B2	2015	2135	18
18	94	B2	2245	2359	18	94	B2	2245	2359	18
19	51	A6	1915	2105	19	51	A6	1915	2105	19

19	155	B7	2130	2215	19	155	B7	2125	2215	19
19	169	B3	2230	2359	19	169	B3	2230	2359	19
20	105	A2	1845	2035	20	105	A2	1845	2035	20
20	117	B2	2055	2359	20	117	B2	2055	2359	20
21	66	A2	1840	1930	21	66	A2	1840	1930	21
21	141	A2	2030	2100	21	141	A2	2030	2100	21
21	111	A3	2215	2359	21	111	A3	2215	2359	21
22	162	B7	1950	2230	22	162	B7	1950	2230	22
22	156	B7	2240	2359	22	156	B7	2240	2359	22
23	38	A2	1830	2105	23	38	A2	1830	2105	23
23	84	A3	2215	2359	23	84	A3	2215	2359	23
24										
25										
26	29	B7	1705	1930	26	29	B7	1705	1930	26
26	150	B3	1940	2315	26	150	B3	1940	2315	26
27	5	B7	2100	2300	27	5	B7	2100	2300	27
28	172	B7	2205	2359	28	172	B7	2205	2359	28
29	78	B6	1945	2200	29	78	B6	1915	2130	29
29	80	A4	2245	2359	29	80	A4	2245	2359	29
30	131	B7	1805	2000	30	131	B7	1825	2000	30
30						47	B7	2025	2145	30
30	13	B3	2150	2359	30	13	B3	2150	2359	30
31	154	B8	1755	1920	31	154	B8	1755	1920	31
31	122	B7	1925	2150	31	122	B7	1955	2220	31
31	48	B8	2225	2359	31	48	B8	2225	2359	31
32	99	B3	1650	2105	32	132	B3	2145	2359	32
32	132	B3	2145	2359	32					
33	72	A4	1910	2035	33	72	A4	1910	2035	33
33	123	B8	2140	2340	33	123	B8	2135	2330	33
34	115	B7	1850	2359	34	115	B7	1900	2359	34
Remote Stand										

(Continued)

GATE	Case 4					Case 5				
	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment	Flight LEG	Aircraft Type	Actual Arrival Time	Actual Departure Time	Recovery Assignment
1	140	B2	1900	2015	1	140	B2	1920	2035	1
1	79	A4	2055	2245	1	79	A4	2055	2245	1
1	142	B2	2320	2359	1	142	B2	2320	2359	1
2	34	A2	1915	2000	2	34	A2	1750	1930	2
2	30	B6	2015	2145	2	30	B6	2015	2145	2
2	106	A2	2225	2359	2	106	A2	2220	2359	2
2										
3	121	B7	1710	1920	3	121	B7	1700	1930	3
3	168	B3	1925	2045	3	12	B7	2025	2140	3
3	52	B7	2145	2359	3	52	B3	2145	2359	3
3										
4	171	B3	1755	2100	4	171	B3	1750	2100	4
4	42	A5	2135	2210	4	43	B7	2220	2359	4
4	43	B7	2220	2359	4					
5	19	B3	1810	2155	5	19	B3	1800	2155	5
5	31	B3	2205	2359	5	31	B3	2205	2359	5
6	83	A3	1800	1920	6	83	A3	1800	1935	6
6	57	A3	2205	2359	6	57	A3	2205	2359	6
7	161	A2	1750	1920	7	161	A2	1925	2015	7
8	155	B7	2130	2235	8	169	B3	2240	2359	8
						47	B7	2100	2225	8
9										
10	128	B7	2120	2359	10	168	B3	1925	2100	10
						128	B7	2120	2359	10
11	100	B7	2115	2240	11	100	B7	2120	2240	11
12	92	B2	1810	1920	12	92	B2	1810	1920	12
12	110	A2	2000	2105	12	110	A2	2000	2105	12

12	35	A2	2225	2359	12	35	A2	2225	2359	12
13	4	B7	1830	2000	13	4	B7	1830	2030	13
13	20	B3	2140	2325	13	20	B3	2140	2325	13
13	21	B7	2335	2359	13	21	B7	2335	2359	13
14	127	B8	1740	2030	14	127	B8	1750	2030	14
14	67	B3	2100	2300	14	67	B3	2100	2255	14
14	6	B7	2320	2359	14	6	B7	2320	2359	14
15	41	B3	1625	2100	15	41	B3	1625	2050	15
15	73	B3	2130	2330	15	73	B3	2130	2330	15
16	61	B3	1925	2359	16	61	B3	1915	2359	16
17	173	B2	0000	2359	17	173	B2	0000	2359	17
18	109	B2	1850	1955	18	109	B2	1845	1935	18
18	93	B2	2055	2155	18	93	B2	2015	2135	18
18	94	B2	2250	2359	18	94	B2	2245	2359	18
19	51	A6	1915	2105	19	51	A6	1915	2105	19
19						155	B7	2125	2245	19
19	169	B3	2230	2359	19					
20	105	A2	1845	2035	20	105	A2	1850	2035	20
20	117	B2	2055	2359	20	117	B2	2055	2359	20
21	66	A2	1845	1950	21	66	A2	1840	1930	21
21	141	A2	2055	2100	21	141	A2	2030	2100	21
21	111	A3	2215	2359	21	111	A3	2220	2359	21
22	162	B7	2000	2230	22	162	B7	1950	2230	22
22	156	B7	2240	2359	22	156	B7	2240	2359	22
23	38	A2	1830	2105	23	38	A2	1830	2105	23
23	84	A3	2215	2359	23	84	A3	2215	2359	23
24										
25										
26	29	B7	1705	1930	26	29	B7	1725	1930	26
26	150	B3	1935	2315	26	150	B3	1935	2315	26
27	5	B7	2100	2300	27	5	B7	2100	2300	27
28	12	B3	2035	2140	28	172	B7	2205	2359	28

	172	B7	2205	2359	28					
29	78	B6	1915	2100	29	78	B6	1915	2100	29
29	80	A4	2245	2359	29	80	A4	2245	2359	29
30	131	B7	1805	2000	30	131	B7	1835	2000	30
30	47	B7	2025	2145	30	47				
30	13	B3	2150	2359	30	13	B3	2150	2359	30
31	154	B8	1755	1920	31	154	B8	1755	1920	31
31	122	B7	1925	2210	31	122	B7	1925	2150	31
31	48	B8	2225	2359	31	48	B8	2225	2359	31
32	99	B3	1700	2105	32	99	B3	1710	2105	32
32	132	B3	2200	2359	32	132	B3	2145	2359	32
33	72	A4	1910	2035	33	72	A4	1910	2035	33
33	123	B8	2135	2330	33	123	B8	2135	2330	33
34	115	B7	1850	2359	34	115	B7	1850	2359	34
Remote Stand						42	A5	2140	2240	Remote

Appendix IX Recovery Solutions Under Different Delay Choices

Type	Flight Leg	Original Gate Assignment	Gate Recovery Solution According to Actual Flight Schedule					
			4 Delay Choices Model (Max Delay: 20mins)		3 Delay Choices Model (Max Delay: 15mins)		2 Delay Choices Model (Max Delay: 10mins)	
			Gate Reassignment by Recovery Model	Delay Choice Used for flight	Gate Reassignment by Recovery Model	Delay Choice Used for flight	Gate Reassignment by Recovery Model	Delay Choice Used for flight
Flight	1	19	19	0	19	0	19	0
	2	5	5	0	5	0	5	0
	3	5	5	0	5	0	5	0
	4	13	13	4	13	0	13	0
	5	27	27	0	27	0	27	0
	6	14	14	3	14	3	11	0
	7	4	4	0	4	0	4	0
	8	19	19	0	19	0	19	0
	9	19	19	0	19	0	19	0
	10	3	3	0	3	0	3	0
	11	33	33	0	33	0	33	0
	12	3	3	0	3	0	3	0
	13	30	30	0	30	0	30	0
	14	30	30	0	30	0	30	0
	15	16	16	0	16	0	16	0
	16	31	31	0	31	0	31	0
	17	31	31	0	31	0	31	0
	18	14	14	0	14	0	14	0
	19	5	5	0	5	0	5	0
	20	13	13	0	13	0	13	0
	21	13	13	0	13	0	13	0
	22	31	31	0	31	0	31	0
	23	31	31	0	31	0	31	0
	24	12	12	0	12	0	12	0
	25	19	19	0	19	0	19	0
	26	19	19	0	19	0	19	0
	27	18	18	0	18	0	18	0
	28	29	29	0	29	0	29	0
	29	26	26	0	26	0	26	0
	30	2	2	0	2	0	2	0
	31	5	5	0	5	0	5	0
	32	9	9	0	9	0	9	0
	33	29	29	0	29	0	29	0
	34	2	2	2	2	2	2	2
	35	12	12	0	12	0	12	0
	36	12	12	0	12	0	12	0
	37	29	29	0	29	0	29	0
	38	23	23	0	23	0	23	0
	39	32	32	0	32	0	32	0

	40	14	14	0	14	0	14	0
	41	15	15	0	15	0	15	0
	42	4	4	3	4	3	8	0
	43	4	4	1	4	1	4	0
	44	14	14	0	14	0	14	0
	45	34	34	0	34	0	34	0
	46	16	16	0	16	0	8	0
	47	30	30	0	30	0	30	0
	48	31	31	0	31	0	31	0
	49	22	22	0	22	0	22	0
	50	13	13	4	13	0	13	0
	51	19	19	1	19	1	19	1
	52	3	3	0	3	0	3	0
	53	1	1	0	1	0	1	0
	54	32	32	4	7	0	7	0
	55	23	23	0	23	0	23	0
	56	20	20	0	20	0	20	0
	57	6	6	0	6	0	6	0
	58	26	26	0	26	0	26	0
	59	14	14	0	14	0	14	0
	60	22	22	3	22	3	22	0
	61	16	16	3	16	3	16	0
	62	5	5	0	5	0	5	0
	63	8	8	0	8	0	8	0
	64	30	30	0	30	0	30	0
	65	19	19	2	19	2	19	2
	66	21	21	0	21	0	21	0
	67	14	14	0	14	0	14	0
	68	27	10	0	27	0	27	0
	69	5	5	0	5	0	5	0
	70	4	4	0	4	0	4	0
	71	4	4	0	4	0	4	0
	72	33	33	0	33	0	33	0
	73	15	15	0	15	0	15	0
	74	21	21	0	21	0	21	0
	75	29	29	0	29	0	29	0
	76	6	6	0	6	0	6	0
	77	1	1	0	1	0	1	0
	78	29	29	0	29	0	29	0
	79	1	1	0	1	0	1	0
	80	29	29	0	29	0	29	0
	81	29	29	0	29	0	29	0
	82	21	21	0	21	0	21	0
	83	6	6	0	6	0	6	0
	84	23	23	0	23	0	23	0
	85	20	20	0	20	0	20	0
	86	3	3	0	3	0	3	0
	87	18	18	0	18	0	18	0

	88	18	18	0	18	0	18	0
	89	18	18	0	18	0	18	0
	90	1	1	0	1	0	1	0
	91	1	1	0	1	0	1	0
	92	12	12	0	12	0	12	0
	93	18	18	0	18	0	18	0
	94	18	18	0	18	0	18	0
	95	3	3	0	3	0	3	0
	96	3	3	0	3	0	3	0
	97	15	15	0	15	0	15	0
	98	3	3	0	3	0	3	0
	99	32	32	0	32	0	32	0
	100	11	11	0	11	0	11	0
	101	2	2	0	2	0	2	0
	102	2	2	0	2	0	2	0
	103	2	2	0	2	0	2	0
	104	2	2	0	2	0	2	0
	105	20	20	0	20	0	20	0
	106	2	2	0	2	0	2	0
	107	18	18	0	18	0	18	0
	108	15	15	0	15	0	15	0
	109	18	18	0	18	0	18	0
	110	12	12	0	12	0	12	0
	111	21	21	0	21	0	21	0
	112	11	11	0	10	0	10	0
	113	13	13	0	13	0	13	0
	114	22	22	0	22	0	10	0
	115	34	34	0	34	0	34	0
	116	6	6	0	6	0	6	0
	117	20	20	0	20	0	20	0
	118	24	24	0	24	0	24	0
	119	20	20	0	20	0	20	0
	120	10	27	0	11	0	11	0
	121	3	3	0	3	0	3	0
	122	31	31	0	31	0	31	0
	123	33	33	0	33	0	33	0
	124	30	30	0	30	0	30	0
	125	30	30	0	30	0	30	0
	126	30	30	0	30	0	30	0
	127	14	14	0	14	0	14	0
	128	10	10	0	10	0	10	0
	129	4	4	0	4	0	4	0
	130	4	4	0	4	0	4	0
	131	30	30	0	30	0	30	0
	132	32	32	0	32	0	32	0
	133	1	1	0	1	0	1	0
	134	1	1	0	1	0	1	0
	135	13	13	0	13	0	13	0

	136	13	13	0	13	0	13	0
	137	19	19	0	19	0	19	0
	138	18	18	0	18	0	18	0
	139	18	18	0	18	0	18	0
	140	1	1	0	1	0	1	0
	141	21	21	0	21	0	21	0
	142	1	1	0	1	0	1	0
	143	13	13	0	13	0	13	0
	144	19	19	0	19	0	19	0
	145	19	19	0	19	0	19	0
	146	3	3	0	3	0	3	0
	147	19	19	0	19	0	19	0
	148	32	32	0	32	0	32	0
	149	19	19	0	19	0	19	0
	150	26	26	0	26	0	26	0
	151	28	28	0	28	0	28	0
	152	16	16	0	16	0	16	0
	153	13	13	0	7	0	7	0
	154	31	31	0	31	0	31	0
	155	19	19	0	19	0	19	0
	156	22	8	0	8	0	8	0
	157	14	14	0	14	0	14	0
	158	31	31	0	31	0	31	0
	159	20	20	0	20	0	20	0
	160	14	14	0	14	0	14	0
	161	2	2	0	2	0	2	0
	162	22	22	0	22	0	22	0
	163	15	15	0	15	0	15	0
	164	13	13	0	13	0	13	0
	165	22	22	1	22	1	22	1
	166	5	5	0	5	0	5	0
	167	31	31	0	31	0	31	0
	168	3	3	0	3	0	3	0
	169	19	19	0	19	0	19	0
	170	33	33	0	33	0	33	0
	171	4	4	0	4	0	4	0
	172	28	28	0	28	0	28	0
Gate Maintenance	173	17	17	0	17	0	17	0
	174	12	12	0	12	0	12	0
	175	10	10	0	10	0	10	0
	176	11	11	0	11	0	11	0
	177	23	23	0	23	0	23	0
	178	24	24	0	24	0	24	0
	179	26	26	0	26	0	26	0
	180	34	34	0	34	0	34	0
Total Number of Gate Changes			**3**		**6**		**8**	
Total Number of Flights Using Delay Choice			**12**		**9**		**4**	

(Continued)

Type	Flight Leg	Original Gate Assignment	Real-time Gate Recovery Solution According to Actual Flight Schedule			
			1 Delay Choice Model (Max Delay: 5mins)		No Delay Choice Model	
			Gate Reassignment by Recovery Model	Delay Choice Used for flight	Gate Reassignment by Recovery Model	Delay Choice Used for flight
Flight	1	19	19	0	19	0
	2	5	5	0	5	0
	3	5	5	0	5	0
	4	13	13	0	13	0
	5	27	27	0	27	0
	6	14	11	0	11	0
	7	4	4	0	4	0
	8	19	19	0	19	0
	9	19	19	0	19	0
	10	3	3	0	3	0
	11	33	33	0	33	0
	12	3	3	0	3	0
	13	30	30	0	30	0
	14	30	30	0	30	0
	15	16	16	0	16	0
	16	31	31	0	31	0
	17	31	31	0	31	0
	18	14	14	0	14	0
	19	5	5	0	5	0
	20	13	13	0	13	0
	21	13	13	0	13	0
	22	31	31	0	31	0
	23	31	31	0	31	0
	24	12	12	0	12	0
	25	19	19	0	19	0
	26	19	19	0	19	0
	27	18	18	0	18	0
	28	29	29	0	29	0
	29	26	26	0	26	0
	30	2	2	0	2	0
	31	5	5	0	5	0
	32	9	9	0	9	0
	33	29	29	0	29	0
	34	2	7	0	7	0
	35	12	12	0	12	0
	36	12	12	0	12	0
	37	29	29	0	29	0
	38	23	23	0	23	0
	39	32	32	0	32	0
	40	14	14	0	14	0
	41	15	15	0	15	0
	42	4	8	0	8	0

	43	4	4	0	4	0
	44	14	14	0	14	0
	45	34	34	0	34	0
	46	16	10	0	8	0
	47	30	30	0	30	0
	48	31	31	0	31	0
	49	22	22	0	22	0
	50	13	13	0	13	0
	51	19	19	1	19	0
	52	3	3	0	3	0
	53	1	1	0	1	0
	54	32	7	0	7	0
	55	23	23	0	23	0
	56	20	20	0	20	0
	57	6	6	0	6	0
	58	26	26	0	26	0
	59	14	14	0	14	0
	60	22	22	0	22	0
	61	16	16	0	16	0
	62	5	5	0	5	0
	63	8	8	0	8	0
	64	30	30	0	30	0
	65	19	19	0	19	0
	66	21	21	0	21	0
	67	14	14	0	14	0
	68	27	27	0	27	0
	69	5	5	0	5	0
	70	4	4	0	4	0
	71	4	4	0	4	0
	72	33	33	0	33	0
	73	15	15	0	15	0
	74	21	21	0	21	0
	75	29	29	0	29	0
	76	6	6	0	6	0
	77	1	1	0	1	0
	78	29	29	0	29	0
	79	1	1	0	1	0
	80	29	29	0	29	0
	81	29	29	0	29	0
	82	21	21	0	21	0
	83	6	6	0	6	0
	84	23	23	0	23	0
	85	20	20	0	20	0
	86	3	3	0	3	0
	87	18	18	0	18	0
	88	18	18	0	18	0
	89	18	18	0	18	0
	90	1	1	0	1	0

	91	1	1	0	1	0
	92	12	12	0	12	0
	93	18	18	0	18	0
	94	18	18	0	18	0
	95	3	3	0	3	0
	96	3	3	0	3	0
	97	15	15	0	15	0
	98	3	3	0	3	0
	99	32	32	0	32	0
	100	11	11	0	11	0
	101	2	2	0	2	0
	102	2	2	0	2	0
	103	2	2	0	2	0
	104	2	2	0	2	0
	105	20	20	0	20	0
	106	2	2	0	2	0
	107	18	18	0	18	0
	108	15	15	0	15	0
	109	18	18	0	18	0
	110	12	12	0	12	0
	111	21	21	0	21	0
	112	11	10	0	10	0
	113	13	13	0	13	0
	114	22	11	0	10	0
	115	34	34	0	34	0
	116	6	6	0	6	0
	117	20	20	0	20	0
	118	24	24	0	24	0
	119	20	20	0	20	0
	120	10	11	0	11	0
	121	3	3	0	3	0
	122	31	31	0	31	0
	123	33	33	0	33	0
	124	30	30	0	30	0
	125	30	30	0	30	0
	126	30	30	0	30	0
	127	14	14	0	14	0
	128	10	10	0	10	0
	129	4	4	0	4	0
	130	4	4	0	4	0
	131	30	30	0	30	0
	132	32	32	0	32	0
	133	1	1	0	1	0
	134	1	1	0	1	0
	135	13	13	0	13	0
	136	13	13	0	13	0
	137	19	9	0	9	0
	138	18	18	0	18	0

	139	18	18	0	18	0
	140	1	1	0	1	0
	141	21	21	0	21	0
	142	1	1	0	1	0
	143	13	13	0	13	0
	144	19	19	0	19	0
	145	19	19	0	19	0
	146	3	3	0	3	0
	147	19	19	0	19	0
	148	32	32	0	32	0
	149	19	19	0	10	0
	150	26	26	0	26	0
	151	28	28	0	28	0
	152	16	16	0	16	0
	153	13	7	0	7	0
	154	31	31	0	31	0
	155	19	19	0	19	0
	156	22	8	0	8	0
	157	14	14	0	14	0
	158	31	31	0	31	0
	159	20	20	0	20	0
	160	14	14	0	14	0
	161	2	2	0	2	0
	162	22	22	0	22	0
	163	15	15	0	15	0
	164	13	13	0	13	0
	165	22	22	1	27	0
	166	5	5	0	5	0
	167	31	31	0	31	0
	168	3	3	0	3	0
	169	19	19	0	19	0
	170	33	33	0	33	0
	171	4	4	0	4	0
	172	28	28	0	28	0
Gate Maintenance	173	17	17	0	17	0
	174	12	12	0	12	0
	175	10	10	0	10	0
	176	11	11	0	11	0
	177	23	23	0	23	0
	178	24	24	0	24	0
	179	26	26	0	26	0
	180	34	34	0	34	0
Total Number of Gate Changes			**11**		**13**	
Total Number of Flights Using Delay Choice			**2**		**0**	